NUTRIENT REQUIREMENTS OF DOGS AND CATS

ANIMAL NUTRITION SERIES

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NUTRIENT REQUIREMENTS OF DOGS AND CATS

Ad Hoc Committee on Dog and Cat Nutrition

Committee on Animal Nutrition

Board on Agriculture and Natural Resources

Division on Earth and Life Studies

National Research Council

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

1 - 2

THE NATIONAL ACADEMIES PRESS • 500 Fifth Street, N.W. • Washington, DC 20001

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This study was supported by the National Institutes of Health under Agreement No. IR24RR142238-01, the Food and Drug Administration under Agreement No. FD-R001887-01, and the Pet Food Institute. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

Library of Congress Cataloging-in-Publication Data

National Research Council (U.S.). Ad Hoc Committee on Dog and Cat Nutrition.
Nutrient requirements of dogs and cats / Ad Hoc Committee on Dog and Cat Nutrition, Committee on Animal Nutrition, Board on Agriculture and Natural Resources, Division on Earth and Life Studies, National Research Council.—[Rev. ed.].
p. cm.
Includes bibliographical references and index.
ISBN 0-309-08628-0 (hardcover)—ISBN 0-309-50733-2 (pdf) 1. Dogs—Nutrition. 2. Cats—Nutrition. 3. Dogs—Food. 4. Cats—Food. I. Title.
SF427.4N38 2006
636.7'0852—dc22

2005037411

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu.

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Printed in the United States of America
First Printing, May 2006
Second Printing, November 2006

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Preface

In 2000, the National Research Council Committee on Animal Nutrition convened the ad hoc Committee on Nutrient Requirements of Dogs and Cats to revise the 1985 and 1986 publications on *Nutrient Requirements of Dogs* and *Nutrient Requirement of Cats*, respectively. The task presented to the committee was as follows:

> An *ad hoc committee* of the Committee on Animal Nutrition will revise the 1985 and 1986 publications on *Nutrient Requirements of Dogs* and *Nutrient Requirements of Cats*. These two publications, originally published as two separate documents, will be revised into a single report. The new report will provide updated estimates of requirements for all nutrients and will contain discussions of nutrient metabolism, toxicity, deficiency, and nutritionally related disease in both dogs and cats. Information on impacts of physiologic status, temperature, breed, age, and environment on nutrient requirements will also be included. The revised report will address unique biological characteristics affecting nutrient digestion and utilization. General considerations regarding feed ingredients, diet formulation, and feed processing and manufacturing will be presented. Principles of feeding pet and laboratory animals will be addressed.

Throughout the study process, the committee sought input from various sources. We held public meetings in conjunction with professional meetings and invited experts to speak with us as we worked to complete our task. Over the course of 3 years, the committee held six meetings and four public sessions. We acquired data and information from various public and private organizations. By combining a thorough literature review with a critical analysis of scientific data and professional experiences, the committee developed recommendations that are firmly grounded in science.

The report is organized into 15 chapters, each addressing unique aspects of nutrition for dogs and cats or providing summary tables of requirements and feed ingredients. Each chapter examines literature published since the last editions of *Nutrient Requirements of Dogs* (1985) and *Nutrient Requirements of Cats* (1986). As the committee delved into this task, it became apparent that we needed to examine earlier research as well to formalize the boundaries of knowledge for each topic explored in this report. In some instances—for example, digestive physiology and physical activity—the chapters are essentially new additions requiring a thorough review of literature through many decades.

The committee was also cognizant of the various audiences for this report. The report will be used by professionals in industry and academia for formulating diets and identifying new topics for research. Government officials may use the report as guidance for regulations for pet food labeling. Students and teachers at universities will use the report as a textbook for dog and cat nutrition. Finally, pet owners will use the report in evaluating feeding decisions for their pets. With these varied audiences, the committee chose to err on the side of caution and include adequate detail from the literature cited to provide a clear road map for how the recommendations were derived.

The reader should note that this published report reflects a number of changes made to correct and update an unedited prepublication version of the report. Some values, particularly in Chapter 15, have been revised or deleted based on the availability of new information or to correct errors in calculation. These changes were examined by four independent reviewers and have been approved by the authoring committee and the institution.

Our assignment was a challenging one. We are pleased to provide what we believe is a comprehensive document that will improve both the understanding of dog and cat nutrition and its practical application in feeding dogs and cats.

DONALD C. BEITZ, *Chair*
Ad Hoc Committee on Nutrient
Requirements of Dogs and Cats

Acknowledgments

This new volume represents the integrated efforts of many individuals. The committee thanks everyone who provided input to this study. We thank all those who provided opportunities for our public meetings and who participated in our public sessions. The financial support provided by the National Institutes of Health, Food and Drug Administration, and the Pet Food Institute is gratefully acknowledged.

During the course of its deliberations, the committee sought assistance from several people who gave generously of their time to provide advice and information that was considered in our deliberations. Special thanks are due to Gail Czarnecki-Maulden for extraordinary contribution to the initiation of this study.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report: Leonard S. Bull, North Carolina State University; Wouter Hendriks, Massey University; Kenneth W. Hinchcliff, Ohio State University; Bruce J. Holub, University of Guelph; Daniel T. Hopkins, Purina Mills, Inc. (retired); Randall A. Johnson, Animal Nutrition Consulting; Neal Merchen, University of Illinois, Urbana-Champaign; William Rumpler, U.S. Department of Agriculture; L. Lee Southern, Louisiana State University; C. Edward Stevens, North Carolina State University; Mark Subramanyam, Schering-Plough Animal Health Corp.; Duane E. Ullrey, Michigan State University; and Thomas R. Zeigler, Zeigler Bros., Inc.; and Jürgen Zentec, Veterinary University of Vienna. Four of the reviewers listed above provided comments on changes made to the prepublication draft. Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Joe Knapka, National Institutes of Health (retired), appointed by the Division on Earth and Life Studies. This individual was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Finally, the committee wishes to thank Charlotte Kirk Baer, program director, and Jamie Jonker, program officer, Committee on Animal Nutrition, for their encouragement and cheerful guidance of this project to completion. Their exceptional organizational skills contributed in a major way to the success of the committee. Appreciation also is extended to Stephanie Padgham, Joe Esparza, and Marina Peunova-Connor, project assistants for the study, for their regular communications and helpful provision of supplementary materials. Thanks are also due to Karen Imhof, administrative assistant, who incorporated edits into the final version of the report, and to Robin Schoen, who took the committee through its final deliberations.

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Overview

The National Research Council has published several editions of *Nutrient Requirements of Dogs* and of *Nutrient Requirements of Cats*, with the most recent editions published in 1985 and 1986, respectively. This new volume represents a revision of both of the previous reports.

Nutrient Requirements of Dogs and Cats has used the latest scientific information to provide the requirements for individual nutrients and the scientific basis for the requirements of healthy dogs and cats at several stages of growth and physiological states. The specific nutrients required for normal growth and development and their estimated daily needs have been elucidated in previous editions of the Nutrient Requirements series. This edition contains the latest data on requirements that are based on the utilization of nutrients in ingredients commonly produced and commercially available in dog and cat foods rather than only on purified diets. Because of overlapping use of feed ingredients, as a convenience to readers and for efficient presentation of the scientific basis for nutrient requirements, the Committee on Animal Nutrition recommended combining the dog and cat data that previously had been published separately (National Research Council, 1985, 1986).

Nutrient requirement data presented in this report are derived from peer-reviewed literature. An extensive amount of new research conducted since the previous National Research Council publications on dogs and cats was available for this NRC report, yet several gaps still exist in our knowledge of requirements for specific nutrients. These gaps in our knowledge are noted in the text and by the absence of data in the requirement tables. Tables of ingredient composition are provided so that users can select the most common ingredients for the development of diets that provide adequate intake of the required nutrients for optimal growth, maintenance, gestation, and lactation of dogs and cats.

The report is organized into 15 chapters, each addressing unique aspects of nutrition of dogs and cats, or providing summary tables of requirements and feed ingredients. Each chapter utilizes older well-established literature as well as the new literature published since the last editions of *Nutrient Requirements of Dogs* (1985) and *Nutrient Requirements of Cats* (1986). As the committee delved into its task, it became apparent that the committee needed to examine earlier research as well to formalize the boundaries of knowledge for each topic explored in this publication. In some instances, such as digestive physiology and physical activity, the chapters are essentially new additions requiring a thorough review of literature through many decades.

The committee was also cognizant of the various audiences for this report. The report will be used by professionals in industry and academia for formulating diets and identifying new topics for research. Government officials may use the report as guidance for regulations for pet food labeling. Students and teachers at universities will use the report as a textbook for dog and cat nutrition. Finally, pet owners will use the report in evaluating the feeding decisions for their pets. With these varied audiences, the committee chose to err on the side of caution and include adequate detail from the literature cited to provide a clear roadmap for how the recommendations were derived.

MINIMAL REQUIREMENT, ADEQUATE INTAKE, RECOMMENDED ALLOWANCE, AND SAFE UPPER LIMIT

Data on the daily provision of nutrients to dogs and cats are presented in tabular form at the end of this publication. First, the *Minimal Requirement* is presented and is defined as the minimal concentration or amount of a bioavailable nutrient that will support a defined physiological state. Data on *Adequate Intake* follow *Adequate Intake* is defined as the concentration in the diet or amount required by the animal of a nutrient that is presumed to sustain a given life stage when no *Minimal Requirement* has been demonstrated. Next, the *Recommended Allowance* for each nutrient is presented. The *Recommended Allowance* is defined as the con-

centration or amount of a nutrient in a diet formulated to support a given physiological state. The *Recommended Allowance* is based on the *Minimal Requirement* and, where applicable, includes a bioavailability factor. If no *Minimal Requirement* is available, the *Recommended Allowance* is based on the *Adequate Intake*. Last, data for *Safe Upper Limit*, or the maximal concentration or amount of a nutrient that has not been associated with adverse effects, are presented.

As noted in the footnotes to the requirement tables, the following assumptions were made to standardize the tabulated data. The energy density of the diet for both dogs and cats was assumed to be 4,000 kilocalories (kcal) of metabolizable energy (ME) per kilogram (kg). Requirements for growth of puppies are based on a 5.5-kg puppy that consumes 1,000 kcal of ME per day. Requirements for adult dogs at maintenance are based on a 15-kg adult dog that consumes 1,000 kcal of ME per day. Requirements for gestating and lactating dogs are based on a 22-kg bitch with eight puppies in peak lactation consuming 5,000 kcal of ME per day. Requirements for growth of kittens are based on an 800-g kitten consuming 180 kcal of ME per day, and those for an adult cat at maintenance are based on a 4-kg adult cat consuming 250 kcal of ME per day. Requirements for gestating and lactating cats are based on 4-kg queen with four kittens in peak lactation consuming 540 kcal of ME per day.

For each of the previously mentioned categories of daily nutrient requirement data, units of expression are, in order, (1) amount of nutrient per kilogram of dietary dry matter (DM), which is assumed to contain 4,000 kcal, (2) amount of nutrient per 1,000 kcal of ME, and (3) amount of nutrient per kilogram of body weight to the 0.75 power ($BW^{0.75}$) for dogs, and per kilogram of body weight to the 0.67 power ($BW^{0.67}$) for cats. Expressing a requirement relative to DM or ME is most convenient when formulating a diet, but expressing a requirement relative to metabolic body weight may be more convenient when formulating a diet for an individual dog or cat. Unfortunately, requirements expressed relative to DM change with the energy density of the diet, and, in some instances, requirements expressed relative to ME may change with body weight (BW). These changes are illustrated in the introduction to the nutrient requirement tables in Chapter 15.

Energy requirements are expressed as kcal of ME per kilogram $BW^{0.75}$ per day for dogs at maintenance and for pregnant bitches. For lactating bitches, energy requirements are a function of both $BW^{0.75}$ and BW as well as number of suckling puppies. Daily energy requirements for growing dogs are based on maintenance requirements multiplied by a factor that is a function of the ratio between actual BW and expected mature BW. The equations for energy requirements in dogs are based on data of dogs between 4 and 60 kg of mature weight, except for female reproduction where the majority of data were obtained from dogs between 5 an 25 kg BW. The equations for energy requirements in cats ar based on data of domestic cats between 2.5 and 7 kg o mature weight. Energy requirements for cats at maintenanc are expressed as kcal of ME per kilogram $BW^{0.67}$ per day fo cats with body condition scores equal to or less than 5.0 (o a 9 point scale) and per kilogram $BW^{0.4}$ for cats with bod scores greater than 5.0. Energy requirements for pregnan queens are expressed as a function of $BW^{0.67}$, whereas fo lactating queens, energy requirements are a function of bot $BW^{0.67}$ and BW as well as number of suckling kittens. Dail energy requirements for growing cats are based on mainte nance requirements multiplied by a factor that is a functio of the ratio between actual BW and expected mature BW.

REPORT HIGHLIGHTS

Digestive physiology is examined in Chapter 1. Th chapter, which was not previously published in the dog an cat series, includes three components: (1) digestive com partments and functions; (2) hormonal aspects of digestion and (3) measurement of, and factors affecting, digestibility This description of each species sets the stage for under standing digestive function and nutritional needs of dog and cats.

Chapter 2 addresses feeding behavior of dogs and cats This new chapter examines intake and factors that affec food and water intake, including aspects of feeding behavio and ingestion that are different in dogs and cats. The chap ter includes discussions of how diurnal rhythms, socia behavior, dietary deficiencies, and learned taste aversion are involved in feeding behavior such as quantity of foo eaten, palatability, and dietary choice.

A discussion of specific nutrients begins in Chapter with energy. The chapter examines ways to predict energ content of diets. The basis for energy requirement recom mendations is explored thoroughly through discussions o the basal metabolic rate, diet-induced thermogenesis, an resting fed metabolic rate for both dogs and cats, leading t energy requirement recommendations for maintenance growth, pregnancy, and lactation. The chapter conclude with a discussion of energy deficiency and excess includin body condition score evaluation.

The discussion of energy is followed by a detaile description of carbohydrates and fiber in dog and cat nutri tion (Chapter 4). This discussion is organized around fou types of carbohydrates: (1) absorbable, (2) digestible (3) fermentable, and (4) nonfermentable carbohydrates Digestion, absorption, utilization, and nutritive value ar explored for each type of carbohydrate. The use of carbohy drates in dog and cat diet formulations ends the chapter.

Chapter 5 addresses fat and fatty acid (lipid) nutritio with emphasis on the metabolism of the various fatty aci

types. This chapter has been updated and expanded to include nomenclature, types and sources of dietary fats, analytical procedures, digestion/absorption of fats, and their digestibility. It also examines the biochemical basis of fatty acid essentiality, describes desaturation and chain elongation pathways, and discusses both structural and functional aspects of dietary lipids. In addition, summaries of studies specifically conducted in dogs and cats with mention of important comparative studies common to other mammalian species also are included. Based on this information, sufficient data are now available to better address the essential nature of both n-6 and n-3 fatty acid types. The chapter culminates with an up-to-date discussion of the requirements, recommendations, and allowances for dogs and cats at their various recognized life stages.

Chapter 6 addresses protein and amino acid nutrition, with emphasis on differences between dogs and cats in digestibility of protein, bioavailability of key limiting amino acids, and control of protein and amino acid metabolism as it relates to protein and amino acid requirements and dietary choice. A new section has been introduced on the use of plasma amino acids to assess essential amino acid status of the animal. Sufficient data were available to determine that the protein and amino acid requirements of 4- to 14-week-old puppies are higher than those puppies over 14 weeks of age; so, separate requirements for these different age groups are given. The section on taurine has been updated to include information on taurine deficiency-induced dilated cardiomyopathy in the dog and the types of diet that contribute to this problem. Finally, differences between dogs and cats in their responses to amino acid excesses and imbalances are discussed.

Mineral nutrition is covered and presented in terms of 12 essential macrominerals and trace minerals in Chapter 7. Acid-base balance is explored for mineral metabolism in dogs and cats. Absorption and bioavailability, deficiencies and excesses, and nutrient recommendations are discussed thoroughly for each essential mineral. Additionally, discussion of seven other minerals (arsenic, boron, chromium, molybdenum, silicon, nickel, and vanadium) explores their potential essentiality, although data on the dog and cat currently do not clearly establish them as essential.

The physiologic functions of 14 fat-soluble and water-soluble vitamins are described in Chapter 8. This discussion includes sections on deficiencies and toxicities for each vitamin. Additional vitamin-like substances, such as inositol, are explored, although none have been demonstrated to be essential for dogs or cats. Finally, vitamin losses in processing and storage of dog and cat foods are examined.

The physiological and biochemical importance of water is outlined in Chapter 9. Regulation of intake, deficiency, and excess is explored for both dogs and cats. The importance of water and feline urinary tract health is discussed. Special considerations for the nutrition and feeding of dogs and cats as laboratory animals are discussed in Chapter 10.

Entirely new to this combined revision are the effects of physical activity and the environment on nutrient requirements of dogs and cats in Chapter 11. Starting with dogs as athletes (sled and racing dogs), effects of sprinting and endurances activities on nutrient requirements are explored. The effects of temperature (both high and low) and high altitude (lower oxygen supply) are examined for energy requirements. Nutrient requirements as a function of amount of exercise and ambient temperatures are discussed for water, protein, fats, carbohydrates, minerals, and vitamins.

The committee presents concepts of diet formulation in Chapter 12. Even though substantial differences in the nutrient requirements of dogs and cats exist, there are many similarities in the techniques used to manufacture their foods. For that reason, petfood processing is addressed in a generic manner and, when appropriate, issues concerning individual species are addressed separately.

The information provided in Chapter 13 on food composition, food processing, and other food constituents is expanded greatly in this volume. Data in Tables 13-1 through 13-8 were compiled from commercial food ingredient suppliers, published literature, and unpublished data provided by university researchers. The tables include means and, when available, the standard deviation and number (N) of samples used to generate those statistics. Users should examine the standard deviation and N when considering using the mean value as an estimate of the nutritional content of a specific food ingredient. Obviously, means derived from a large N will better reflect the total population. Means with a large standard deviation may represent the total population but may be a poor estimate for a specific sample.

Chapter 14 presents an overview of other food constituents that may be used in cat and dog diet formulation. These substances in the diet may affect the structure or function of the body but their absence from the diet does not fit into classical models of nutritional deficiency. Some play vital roles in the normal metabolism of the animal but cannot be deemed essential because the body is capable of synthesizing them from other dietary components. Other substances that may play a role in the normal function of the body must come from an exogenous source, but determinations of essentiality have yet to be established. Chapter 14 also presents an overview of other food constituents intended for technical purposes, such as preservatives.

Nutrient requirements for growth, adult maintenance, gestation, and lactation for dogs and cats are provided in Tables 15-2 through 15-14 (Chapter 15). Estimates are listed for energy, protein and amino acids, fatty acids, macrominerals, trace minerals, and vitamins.

REFERENCES

National Research Council (NRC). 1985. Nutrient Requirements of Dogs. Washington, D.C.: National Academy Press.

National Research Council (NRC). 1986. Nutrient Requirements of Cats. Washington, D.C.: National Academy Press.

The reader should take note that this document reflects a number of changes made to correct and update an unedited prepublication version of this report. Some values, particularly in Chapter 15, have been revised or deleted based on the availability of new information or to correct errors in calculation. These changes were examined by four independent reviewers and have been approved by the authoring committee and the institution. This final version of the report, therefore, supersedes the data contained in the prepublication.

1

Comparative Digestive Physiology of Dogs and Cats

The purpose of this chapter is to provide an overview of the information available on the digestive physiology of dogs and cats. The chapter is divided into three sections: (1) digestive compartments and functions; (2) hormonal aspects of digestion; and (3) measurement of, and factors affecting, digestibility. A number of texts cover in some depth the features of the digestive tracts of dogs and cats. Therefore, no attempt has been made in the first section of this chapter to cite original references dealing with this topic. Rather, the review chapter entitled "Digestion and Absorption" by Maskell and Johnson (1993) published in *The Waltham Book of Companion Animal Nutrition* (I. H. Burger, editor) was used as a guide for describing the digestive compartments of dogs and cats and their functions, as was the textbook *Comparative Physiology of the Vertebrate Digestive System* authored by Stevens and Hume (1995). Supplementing this information are quantitative data reported in reviews by Smeets-Peeters et al. (1998) and Awati (2000) regarding the digestive physiological responses to different types of dog and cat foods. Enzyme activity values, electrolyte concentrations, gastric emptying and intestinal transit times, pH values, secretion characteristics and composition of bile, and absorption rates in different parts of the dog and cat gastrointestinal tracts were compiled from original reference articles. Their reviews focused on research with healthy, adult dogs weighing 10 to 20 kg and on adult cats, and the data related to the oral cavity, stomach, and small intestine primarily. Much of the information cited in the first section of this chapter has been taken from these reviews, and original references are cited where appropriate.

The next section is a compilation of original citations on gastrointestinal hormone characteristics of dogs and cats. The information is in stand-alone tabular format with the following headings: hormone, the cell type that produces the hormone, the location of hormone action, the primary action of the hormone, the stimulus for hormone secretion, the specific hormonal data that have been collected with dogs and cats, and the references. For brevity, no further information beyond that presented in tables is provided.

The final section deals with measurement of nutrient digestibility in dogs and cats and factors affecting this process that are critical to optimal utilization of nutrients in pet foods.

INTRODUCTION

Dogs (Figure 1-1) and cats (Figure 1-2) have a relatively similar digestive tract except for its length. Dogs with a body length of 0.75 m have an intestinal length averaging 4.5 m (small intestine = 3.9 m; large intestine = 0.6 m). Cats with a body length of 0.5 m have an intestinal length of approximately 2.1 m (small intestine = 1.7 m; large intestine = 0.4 m). Intestinal length is one factor that influences the amount of time food resides in the gut. That, in turn, influences the duration of digestion (Maskell and Johnson, 1993).

The digestive tract of the dog or cat has a large absorptive surface area that serves to increase the rate of nutrient digestion as a result of the presence of villi. The surface area per centimeter of intestinal length is similar for the dog and the cat (jejunum, 54 and 50 cm^2; ileum, 38 and 36 cm^2, respectively) (Maskell and Johnson, 1993).

A major difference in the gastrointestinal tracts of dogs and cats is the fact that the dog proximal stomach has a thinner mucous membrane with distinct gastric glands and the distal stomach has a thicker mucous membrane with less distinct glands. The gastric mucosa of the dog and cat stomach is divided into a narrow band of cardiac glandular mucosa and wide bands of proper gastric and pyloric glandular mucosa (Stevens and Hume, 1995). The cardiac and pyloric glandular regions secrete mucus and bicarbonate. The proper gastric glandular region secretes hydrochloric acid and pepsinogen. The feline gastric mucosa is uniform in comparison to that of the canine (Maskell and Johnson, 1993). In the dog, the cecum is a coiled appendage located

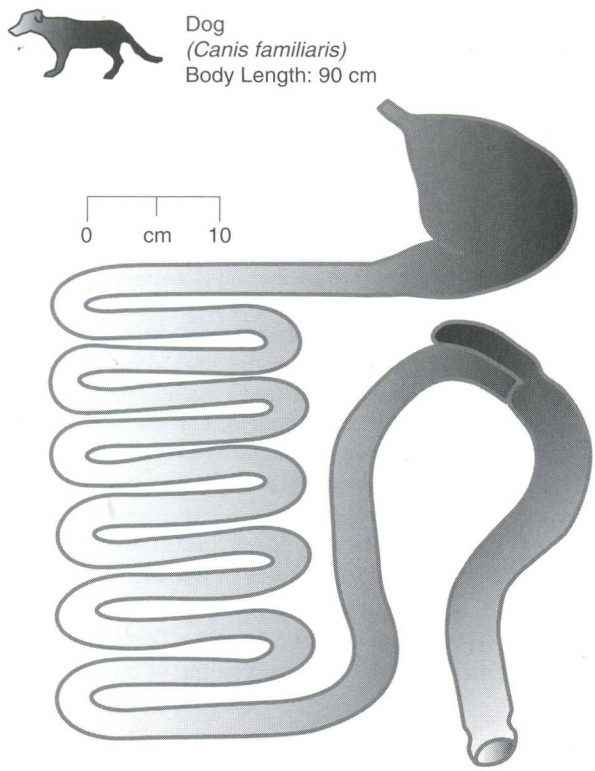

FIGURE 1-1 Dog gastrointestinal tract (Stevens and Hume, 1995).

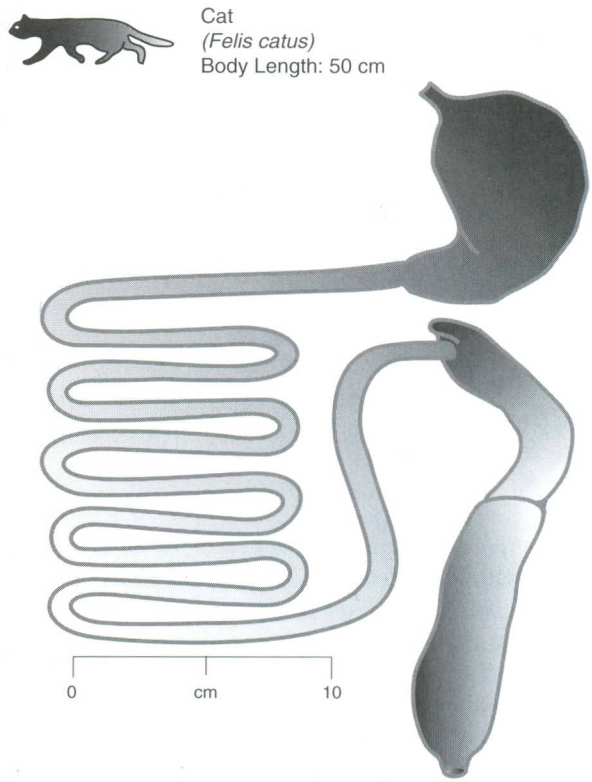

FIGURE 1-2 Cat gastrointestinal tract (Stevens and Hume, 1995).

distal to the ileocecal valve, while in the cat the cecum is not as coiled (Stevens and Hume, 1995).

As explained by Maskell and Johnson (1993)

> Digestion involves a combination of mechanical, chemical, and microbial events, all contributing to the sequential degradation of food components. Mastication and alimentary muscular contractions mechanically diminish the size of ingested food particles. Enzyme-rich digestive fluids secreted into digesta in the stomach and small intestine instigate chemical degradation. Bacteria inhabiting the terminal section of the alimentary canal also produce enzymes capable of chemical digestion of those food components that have escaped hydrolytic digestion anterior in the tract. The actions of the gastrointestinal tract are under both voluntary and involuntary control. Ingestion, chewing, and swallowing are events consciously controlled by the individual. Thereafter, the digestive functions that begin in the back of the mouth with the initiation of swallowing are all reflex events (i.e., not under voluntary control). As food passes from the pharynx via the esophagus to the stomach, sphincters open and close under involuntary nervous control emanating subconsciously from the brain. As food enters the stomach, the reflex response of the gastric muscles is to relax in order to counteract undue increases in intragastric pressure. All digestive secretions in the stomach and intestines are controlled by nervous and hormonal interactions as is the motility of the tract, which propels digesta in peristaltic waves towards the terminal end of the gut.

Comparative studies have revealed a close relationship between intestinal characteristics, the natural feral diet, and nutrient requirements (Buddington, 1996). Cats originate from a family comprised only of strict carnivores (Felidae), whereas dogs are omnivorous.

DIGESTIVE COMPARTMENTS AND FUNCTIONS

Mouth

The process of digestion begins in the mouth. Saliva is secreted during mastication of food by four pairs of salivary glands—the parotids in front of each ear, the mandibular (or submaxillary) gland on each side of the lower jaw, the sublingual glands under the tongue, and the zygomatic gland located in the upper jaw below the eye. The glands are located similarly in the cat (Maskell and Johnson, 1993). Saliva flow is increased by the sight and smell of food. The type of food ingested and its moisture content affect saliva amount and composition. Chauncey et al. (1963) quantified the amount of saliva produced by the parotid gland (0.14-1.40 $mL \cdot min^{-1}$; mean value = 0.55) and the submaxillary gland (0.20-3.84 $mL \cdot min^{-1}$; mean value = 1.31) of the dog. The

composition of saliva varies among the glands and with the rate of salivary flow (Stevens and Hume, 1995). Submaxillary and sublingual glands secrete large amounts of mucus. The parotid glands secrete a serous fluid. The major inorganic ions in saliva are sodium, potassium, and chloride, which are derived from the plasma, and bicarbonate secreted by glandular cells. At high rates of flow, the saliva released into the mouth of the dog and cat has an osmolarity and sodium:potassium ratio similar to blood plasma, but a higher bicarbonate:chloride ratio and pH than plasma. However, at lower rates of flow, the absorptive activities of salivary tubular cells reduce the osmolarity, the sodium:potassium ratio, the chloride and bicarbonate concentrations, and the pH of saliva reaching the mouth. The pH of dog saliva varies between 7.34 and 7.80 (Altman and Dittmer, 1968), whereas the average value for cat saliva is 7.5 (Awati, 2000). Like many species, dogs and cats lack the α-amylase enzyme that would initiate the process of starch digestion.

Average electrolyte concentrations (in millimoles per liter) in dog saliva are as follows: calcium (1.85 in mixed saliva; 4.3 in parotid saliva); chloride (81.9 in parotid saliva); potassium (20.2 in mixed saliva; 11.4 in parotid saliva); sodium (74.1 in mixed saliva; 108 in parotid saliva); and bicarbonate (55 in parotid saliva) (Altman and Dittmer, 1968; Lamas and Scheinin, 1971). Values (millimoles per liter) reported for cats are chloride (16.8-36.0); potassium (7.7-9.2); sodium (24-46); and bicarbonate (11.6-13.6) (Altman and Dittmer, 1968).

A very important function of saliva in the dog is evaporative cooling. Upon intense parasympathetic stimulation, the parotid gland of the dog secretes saliva at 10 times the rate of the human (per gram of gland weight) (Argenzio, 1989). Saliva is hypotonic at low flow rates and becomes increasingly tonic with increasing flow rates. It is nearly isotonic at maximal flow rates.

Esophagus

The esophagus is a short, muscular tube leading from the mouth to the stomach. The esophagus of the dog contains only striated muscle that lends itself to more rapid passage of peristaltic waves (Stevens and Hume, 1995). Esophageal cells produce mucus to lubricate the process of peristalsis that propels food along the digestive tract. These cells are stimulated by the presence of food. Transport of food from the mouth to the stomach takes only a few seconds (Maskell and Johnson, 1993).

Stomach

Functionally, the stomach consists of proximal and distal sections. The proximal stomach expands during the temporary storage of food, allowing consumption of discrete meals rather than many small meals. Since dogs are meal feeders, in contrast to cats who tend to eat small meals, this is of greater importance to the canine (Maskell and Johnson, 1993).

The stomach stores food temporarily and controls the rate of entry of ingesta into the small intestine. It participates in the initial stages of digestion by secreting hydrochloric acid and pepsinogen. Circular muscles in the proximal half of the stomach undergo stationary contractions that mix and macerate the gastric digesta. A pacemaker near the center of the stomach generates waves of muscular contraction over the distal segment of the stomach. These waves of peristaltic contraction aid in passage of digesta through the stomach and, eventually, into the duodenum (Stevens and Hume, 1995).

The concentrations of electrolytes in the gastric juice of dogs are as follows: bicarbonate, 5-33; potassium, 7-28; sodium, 22-155; chloride, 123-173; calcium, 0.5-4; phosphate, 0.026 to 12; and magnesium, 0.021 $mmol \cdot L^{-1}$. Comparable values for cats are potassium, 12-14; sodium, 12-56; chloride, 156-166; calcium, 1-2.5; phosphorus, 0.06-0.19; and nitrogen, 7.1-29.3 $mmol \cdot L^{-1}$ (Altman and Dittmer, 1968).

The major enzymes present in the lumen of the dog stomach are pepsin and lipase. At pH 4, gastric lipase is 13 times more active on long-chain than on short-chain triacylglycerols (Carriere et al., 1991). The lipase is irreversibly inactivated below pH 1.5; its activity also decreases significantly above pH 6.0, and it is completely inactivated at pH 7.0. Lipase is secreted throughout the canine stomach (Carriere et al., 1992). Compared to pancreatic lipase, the contribution of gastric lipase to fat digestion is not great (see Chapter 5).

The activity of pepsin after sham feeding varies fourfold for dogs. Factors responsible for the variability among animals are unknown (Villareal et al., 1955). The amount of pepsin secreted can be influenced by hormones, such as adrenocorticotropic hormone (ACTH), which causes an increase in activity. Pepsin displays optimal activity at pH 2.0 maintained by gastric secretion of hydrochloric acid. Its proteolytic activity decreases when chyme leaves the stomach, since it is irreversibly inactivated at neutral pH (Smeets-Peeters et al., 1998). Because pepsin is most active when the cat or dog has ingested collagen, its activity is more important for initiating the digestion of meat rather than of vegetable protein (Maskell and Johnson, 1993). As such, pepsin may be more important to the cat than the dog. For the cat, the basal secretion rate is 2.7 ± 0.07 $\mu g \cdot min^{-1}$. After meal stimulation, the value increases to 16 ± 4 $\mu g \cdot min^{-1}$ (Descroix-Vagne et al., 1993).

Gastric secretion is influenced by the amount of protein in a meal, by the volume of the meal (Carpentier et al., 1977), and by hormones that indirectly affect the acidity of the stomach contents (ACTH increases hydrochloric acid production [Villareal et al., 1955] and secretin decreases hydrochloric acid production through suppression of the release of gastrin [Jin et al., 1994]). The nervous system also

plays a role in the secretion of hydrochloric acid (Lawson et al., 1994). In the fasting state, the gastric pH of the dog fluctuates little with time, whereas postprandially, there are wavelike patterns (Youngberg et al., 1985). The gastric pH response varies with the type of meal ingested and the buffering capacity of the food. After ingestion of a complete liquid test meal, a pH drop below 4.0 was noticed within 10-20 minutes (Youngberg et al., 1985). With a meat-based diet, a drop in pH to less than 6.0 was found after 60 minutes (Banta et al., 1979; Carriere et al., 1993).

The average pH of the cat stomach is 2.5 ± 0.07 (Brosey et al., 2000). Mechanisms controlling acid secretion occur at three sequential times during digestion (cephalic phase, gastric phase, and intestinal phase) and are described in detail in Argenzio (1989).

Bacterial populations have been isolated from the stomach contents of many simple stomached species (Kearns et al., 1998). Numbers are variable (approximately 10^3 bacteria per milliliter) and are influenced by both diet and environment. Many of these microbes represent transient communities rather than a population of microbes indigenous to this site. They originate from ingested material or from regions proximal to the stomach. Microbial types most often found are Gram positive and aerobic, representing members of the lactic acid bacteria (*Bifidobacterium, Lactobacillus,* and *Streptococcus*). Stomach contents of cats fed a corn-poultry by-product meal or a soybean meal-based diet contained approximately 20 $mmol \cdot L^{-1}$ total short-chain fatty acids (SCFAs) (Brosey et al., 2000).

Gastric Emptying

Smeets-Peeters et al. (1998) summarized the following as affecting the rate of gastric emptying: stomach volume; energy content (Liddle et al., 1988), viscosity, density, and particle size of gastric contents; temperature; body weight; amount of acid in the duodenum; water intake; meal size; and diet type (Goggin et al., 1998). Using duodenally cannulated dogs, the effect of the density of nondigestible solids on gastric emptying was evaluated (Meyer et al., 1985). There was a trend for higher-density particles to empty more slowly. The regulation of emptying by density depends on the intraduodenal concentrations of products of digestion, either monosaccharides, acting through their osmotic effect, or esters of fatty acids, acting on duodenal receptors. Isocaloric concentrations of carbohydrates and triglycerides induce similar gastric emptying patterns (Hunt and Stubbs, 1975).

Reduction of digestible solids to a smaller size accelerates gastric emptying. Indigestible solids are retained in the stomach until digestion of other food components is completed. They do not exit the stomach until powerful, propulsive, gastric contractions in the fasting state take place (Hinder and Kelly, 1977). The stomach appears to be the major site involved in regulation of particulate marker passage through the gastrointestinal tract of dogs (Banta et al., 1979).

Literature values for average gastric half-emptying times for dogs range from 72 to 240 minutes (Burrows et al., 1985; reviewed in Smeets-Peeters et al., 1998). Methodology (intubation with periodic sampling vs. scintigraphy vs. radiography), diet type (dry kibble, canned diet, fresh food, liquid meal) and characteristics (acidity, osmolarity, fat content, tryptophan content), variation among animals, animal's access to water, indicator used, meal size, and fed versus fasting state of the animal are a few of the factors that impact the results obtained. For cats, gastric half-emptying times (minutes) range from 22-25 (fasted state) to 449 for cats fed a canned diet (Chandler et al., 1997). Intermediate values have been reported by Arnbjerg (1992), Sparkes et al. (1997), Goggin et al. (1998), and Chandler et al. (1999).

Small Intestine, Pancreas, and Liver

Most of the enzymatic digestion of food occurs in the small intestine. The resulting monomeric units then are absorbed as they are released from the food along with water, vitamins, and minerals. A 20-kg dog absorbs approximately 3 L of fluid daily. Of that volume, 50 percent is absorbed from the jejunum, 40 percent from the ileum, and 10 percent from the large bowel (Maskell and Johnson, 1993).

Digesta passing from the stomach into the duodenum are neutralized rapidly. Dogs fed cereal- and meat-based diets have an average pH in the proximal duodenum of 6.2 (Banta et al., 1979). Ingestion of large volumes of water by the dog appears to induce acid secretion in the stomach (by stimulation of gastrin release) and to lower the pH to values as low as 1.5 in the lumen of the proximal duodenum. For the cat, the average duodenal pH is 5.7 ± 0.5, while those of the jejunum and ileum are 6.4 ± 0.5 and 6.6 ± 0.8, respectively (Brosey et al., 2000).

Secretion of pancreatic juice into the duodenum is stimulated by movement of acid chyme from the stomach into the small intestine. The large amount of bicarbonate in pancreatic juice and bile results in an increase in pH of digesta passing from the stomach to the duodenum (Banta et al., 1979).

In the duodenum, chyme is mixed with enzymes. Certain enzymes originate from the duodenal mucosa. Other enzymes originate from the pancreas, an organ with two discrete functions: (1) exocrine—secreting enzymes into the gut in addition to bicarbonate salts that optimize luminal pH for pancreatic and intestinal enzyme function, and (2) endocrine—secreting hormones into the blood. Pancreatic enzymes include inactive proteases, lipases, and amylases. Intestinal enzymes located in the luminal brush border and contents of intestinal absorptive cells catalyze the final stages of digestion (Maskell and Johnson, 1993).

Secretin and cholecystokinin, produced by cells of the intestinal mucosa, regulate output of pancreatic juice. Secretin

stimulates the pancreas to increase bicarbonate secretion; its release is caused by the acidity of small intestinal contents. Bicarbonate concentration and pH of pancreatic fluid also are dependent on rate of flow. Cholecystokinin release results from the presence of partially digested food, especially fat and phenylalanine-containing peptides, in the small intestine, and stimulates the release of enzyme-rich juices (Maskell and Johnson, 1993). Key characteristics of dog pancreatic juice are the following: pH, 7.1-8.2; secretion rate, 0.2-1.1 $mL \cdot min^{-1}$; water content, 98 percent; ash content, 8.4-9.7 $g \cdot L^{-1}$; total solids, 14-64 $g \cdot L^{-1}$; bicarbonate, 93-143 $mmol \cdot L^{-1}$; and total nitrogen, 71.4-671.4 $mmol \cdot L^{-1}$ (Altman and Dittmer, 1968). More limited information is available for cats: calcium, 2.3-2.55 $mmol \cdot L^{-1}$ (Altman and Dittmer, 1968); chloride, 67-93 $mmol \cdot L^{-1}$ (Altman and Dittmer, 1968); and amylase, 34.1 ± 6.4 units per 120 minutes (Layer et al., 1985).

The pancreatic juice of dogs possesses antibacterial properties (Rubenstein et al., 1985). The active component is a protein with a molecular weight of approximately 4,000 Da and an alkaline pH optimum. It retains activity until pancreatic juice is diluted at least tenfold. It is resistant to degradation by pancreatic proteases and has bactericidal activity against *Escherichia coli, Shigella, Salmonella,* and *Klebsiella*; it is bacteriostatic for coagulase-positive and negative staphylococci and *Pseudomonas*. It also inhibits growth of *Candida albicans*. Whether it affects groups of microbes considered to be beneficial (e.g., lactobacilli, bifidobacteria, and eubacteria) is not known.

Bile is stored and concentrated in the gallbladder, then released into the intestine in response to the presence of lipids or their digestive end products in the duodenum. Bile from the gallbladder differs in concentration from bile secreted directly from the liver (e.g., pH = 5.18-6.97 vs. 7.1-8.5; dry matter [grams per liter] = 114-246 vs. 23-45; salts [grams per liter] = 79-150 vs. 5-24; cholesterol [grams per liter] = 0.8-1.4 vs. 0.04-0.15, respectively) (Smeets-Peeters et al., 1998). More than 99 percent of bile acids normally are conjugated with taurine to form taurocholic acid, taurodeoxycholic acid, and taurochenodeoxycholic acid in both dogs and cats. In response to food ingestion, the gallbladder contracts, and its pressure and rate of emptying increase. Emptying peaks are found 30 minutes after a meal, and the emptying decreases 2 hours after food ingestion (Madrid et al., 1983; Traynor et al., 1984). Food is an inducer of diurnal rhythms in the gallbladder. These contraction-relaxation cycles are synchronized with periodic dilution-concentration processes (Camello et al., 1991). The gallbladder empties only partially after a meal (5-65 percent). Half-emptying time has been reported to be approximately 47 minutes. Periodic food ingestion plays a role in the daily rhythms of gallbladder bile composition as does duodenal activity (Smeets-Peeters et al., 1998).

Washizu et al. (1990) compared the bile acid composition of the dog and the cat. Values (in milligrams per milliliter) for the cat are taurocholic acid, 97 ± 38; taurodihydroxycholic acid, 22 ± 7; tauroursodeoxycholic acid, 0.03 ± 0.04; taurochenodeoxycholic acid, 3.3 ± 1.2; taurodeoxycholic acid, 4.4 ± 2.5; taurolithocholic acid, 0.04 ± 0.01; glycoursodeoxycholic acid, 0.33 ± 0.38; glycochenodeoxycholic acid, 0.12 ± 0.11; glycocholic acid, 1.5 ± 0.8; and cholic acid, 0.09 ± 0.14. Only the concentration of taurodeoxycholic acid in the cat (4.4 ± 2.5 $mg \cdot mL^{-1}$) was different from that of the dog (10.3 ± 1.5 $mg \cdot mL^{-1}$). The cat obligatorily conjugates bile acids with taurine. Thus, when it is taurine deficient, a high percentage of free cholic acid is found in bile (Rentschler et al., 1986; Hickman et al., 1992).

Small Intestinal Microbiology

The small intestine of the dog has a rather simple microbial population (Kearns et al., 1998). Bacterial numbers rarely exceed 10^4 per milliliter, except for the distal ileum where counts are approximately 10^6 mL^{-1}. Streptococci and lactobacilli are found predominantly in the duodenum and jejunum. In the ileum, the predominant microbes are *Escherichia coli* and anaerobic bacteria. The relatively low number of microbes is due primarily to the influence of gastric acidity and bile, as well as intestinal motility, which allows nonadherent bacteria to pass through the gut. An important function of the microflora of the small intestine is preventing the colonization of pathogenic microorganisms. They accomplish this by competing for available nutrients, controlling oxygen concentrations, and producing antibacterial substances.

In the cat, Johnston et al. (1993) found that total bacterial counts in duodenal juice ranged from 2.2×10^5 to 1.6×10^8 colony forming units (CFU) per milliliter with anaerobic counts between 7.5×10^4 and 1.1×10^8. The most commonly isolated anaerobes were *Bacteroides, Eubacteria,* and *Fusobacteria*, while *Pasteurella* species were the most common aerobic bacteria isolated. These findings showed that, compared to the dog, clinically healthy cats fed a commercial canned diet can have relatively high bacterial counts in undiluted juice obtained from the proximal small intestine. Indeed, the numbers of bacteria in these cats fulfill the established criteria for small intestinal bacterial overgrowth in dogs. Species characteristics that may influence the intestinal flora include gastric or pancreatic secretions, intestinal motility, local immunity, and bile composition. These mechanisms have been corroborated by the studies of Gruffydd-Jones et al. (1998). Brosey et al. (2000) reported the duodenum, jejunum, and ileum of cats fed a corn-poultry by-product meal or a soybean meal diet contained 30, 29, and 41 $mmol \cdot L^{-1}$ total SCFAs, respectively.

Using a diet very similar to that of Brosey et al. (2000), Strickling et al. (2000) found total SCFA concentrations in the dog ileum of 598 $\mu mol \cdot g^{-1}$ dry matter (79 $\mu mol \cdot g^{-1}$ as-is digesta). With regard to ileal microbes, they reported the following concentrations (log CFU per gram of dry matter) of

bacteria: *Clostridium perfringens,* 4.8; bifidobacteria, 10.4; lactobacilli, 9.4; aerotolerant anaerobes, 10.5; *E. coli,* 6.3; and coliforms, 6.7. These values are higher than those reported by Kearns et al. (1998).

The influence of small intestinal microbes on nutrient requirements of the dog and cat remains to be determined, as does the potential of diet to alter requirements by modification of the intestinal flora. A case in point is taurine, which is impacted by heat processing (120°C; 83 minutes) of a commercial diet, resulting in increased amounts reaching the lower gut. Heat processing may affect taurine status of cats by perhaps stimulating microbial overgrowth in the small intestine. Bacterial overgrowth could occur if heat processing decreased digestibility of a portion of the diet and increased available substrate for microorganisms (Hickman et al., 1990).

Small Intestinal Transit Time

Movement of digesta through the small intestine is influenced by physical and nutritional characteristics of the diet (Clemens and Stevens, 1980). Motility of the intestine can be influenced by factors such as food components, hormones, and the nervous system. Digesta passage can be determined by administration of markers that are not digested, secreted, absorbed, or adsorbed with subsequent measurement of the rate of food or digesta fluid or particle passage through the gastrointestinal tract. Transit time is the time from the administration of a food or food marker to its appearance in feces. Mean retention time is the time required for the average particle or fluid marker to be excreted after administration of a pulse dose (Stevens and Hume, 1995). Results of transit experiments can be misleading because a single value in no way indicates how the bulk of material moved through the gastrointestinal tract, nor does it consider the structure, volume, or length of the gastrointestinal tract. Published values for small intestinal transit times vary widely. For example, Miyabayashi et al. (1986), using five dogs orally dosed with a 60 percent w/v barium sulfate solution, reported a transit time of 73.0 ± 16.4 minutes (range, 30-120 minutes) and a small intestinal emptying time of 214 ± 25.1 minutes (range, 180-300 minutes). In their study, small intestinal transit time and emptying time correlated positively with gastric emptying time.

In unfed dogs, radiolabeled saline reached the cecum in just 37 minutes (Quigley and Thompson, 1993). Addition of macronutrients, however, slowed the movement of intestinal contents (Schemann and Ehrlein, 1986). Johnson et al. (1997) found that the mean rate of movement of chyme was 5 $cm \cdot min^{-1}$ in the jejunum and 13 $cm \cdot min^{-1}$ in the ileum. If the length of the small intestine in a 19-kg dog is 360 cm as suggested by Quigley and Thompson (1993), transiting the small intestine should take about 1 hour. This is in agreement with data of Hill et al. (2000) who demonstrated that chyme first appeared at the ileocolic junction on average 1 hour after a meal in dogs fed a canned diet once daily, and that 15, 50, and 95 percent of chyme reached the terminal ileum after 2.5, 5.5, and 12 hours, respectively. In dogs with midintestinal cannulas, however, transit times from duodenum to midintestine after a small steak meal were 49, 62, and 78 minutes for polyethylene glycol, 0.5-mm, and 2-mm liver particles, respectively (Williams et al., 1984). Other methodologies suggest a longer mean or median orocecal transit time in fed dogs: 105-135 minutes using the breath hydrogen test; 180 minutes using the sulfasalazine, sulfapyridine test; or 150 minutes using radiolabeled sulfacolloid (Papasouliotis et al., 1993, 1995; Roussel et al., 1996). These times correspond to the time for collection of 15 percent of total chyme in the study of Hill et al. (2000), suggesting that a certain amount of chyme, equivalent to 15 percent of the total, may have to accumulate in the colon before breath hydrogen or marker can be detected.

For the cat, a small intestinal transit time of between 135 and 183 minutes was reported by Chandler et al. (1999).

Large Intestine

The primary role of the large intestine of dogs and cats is to absorb electrolytes and water and to serve as an environment for microbial fermentation of nutrients that escape digestion and absorption by the small intestine. In both species, the large intestine is relatively short (0.6 m in dogs; 0.4 m in cats) (Maskell and Johnson, 1993). The large intestine consists of the cecum, colon, and rectum. The colon makes up the majority of the large intestine and consists of three sections—the ascending, transverse, and descending colon. The large intestine has no villi, and its surface is flat. Straight, tubular glands, the crypts of Lieberkuhn, extend from the serosal surface through the mucosa. They contain mucus cells in their deepest portions and both mucus and epithelial cells near the surface. The mucus is alkaline (from bicarbonate) and its function is to protect the large intestinal mucosa from mechanical and chemical injury. The mucus provides lubrication to facilitate passage of feces, and the bicarbonate ions neutralize acids produced by bacterial fermentation (Maskell and Johnson, 1993).

The residence time of undigested food in the large intestine of the dog and cat is approximately 12 hours (Maskell and Johnson, 1993). Burrows and Merritt (1983) studied the influence of α-cellulose additions to dog diets on myoelectric activity of proximal canine colon. The proximal colon was chosen because most water absorption occurs in this part of the organ, and the effects of fiber on activity responsible for both mixing and propulsion are perhaps greatest at this location. The major finding of this study was that increased intake of the α-cellulose (up to 9 percent by weight of a canned, commercial diet) decreased myoelectric spike activity in the proximal colon of the dog through an effect on the migrating spike burst. A variety of extrinsic neural and hormonal factors has been known to influence colonic

motility and to these must be added the effect of luminal bulk. Since dietary fiber increases fecal bulk and weight, the proximal colon of the dog probably contracts more effectively as luminal bulk increases.

Using colonic transit scintigraphy, Krevsky et al. (1988) found that the cecum and ascending colon of cats emptied rapidly, with a half-emptying time of 1.68 ± 0.56 hours. These results suggest that the cecum and ascending colon may not be an important region for storage in the cat. Also, it is possible that the relatively short length of the cecum and ascending colon is responsible for its rapid emptying. Unlike the cecum and ascending colon, significant storage occurred in the transverse colon, suggesting that the transverse colon of the cat is the important region for mixing, storage, and dehydration, and it is this region that appears to function as a distal storage site prior to defecation. These findings are consistent with the observation of retrograde peristaltic contractions originating in the transverse colon that have been described repeatedly for many years.

Only about 8 percent of the total digestion of food occurs in the large intestine of the dog (Drochner and Meyer, 1991), although this figure varies with diet. Using 25 diets fed to dogs cannulated in the terminal ileum, Meyer and Schunemann (1989) reported that with highly digestible diets, colonic digestibility accounted for 1 to 4 percent of total digestibility, whereas with diets containing legumes and certain types of starches (e.g., tapioca), colonic digestibility ranged from 12 to 24 percent of total digestibility. The highest colonic digestibility values occurred when dogs were fed diets containing raw potato starch and lactose.

The large intestine contains a complex microbial ecosystem comprised of many genera and several hundred species of bacteria. Most of the bacteria in the healthy intestine are anaerobic, and the main bacterial genera present in a healthy dog or cat are *Streptococcus*, *Lactobacillus*, *Bacteroides*, and *Clostridium* (Maskell and Johnson, 1993). Dietary ingredients can affect the bacterial composition of the large intestine.

Colonic bacteria ferment dietary nutrients and endogenous secretions that escape digestion and absorption in the small intestine. Examples of these include resistant starch, non-starch polysaccharides, unabsorbed sugars, oligosaccharides, dietary protein, endogenous enzymes, and mucus. The proximal portion of the human colon generally is rich in carbohydrate substrates, while protein fermentation prevails in the distal colon (Macfarlane et al., 1992). This is probably the case for both dog and cat. The primary end products of bacterial fermentation and metabolism are SCFAs (acetate, propionate, butyrate), lactate, carbon dioxide, and hydrogen gas. Brosey et al. (2000) reported total SCFA concentrations in the proximal and distal portions of the colon of cats fed a corn-poultry by-product meal or soybean meal diet of 109 and 131 $mmol \cdot L^{-1}$, respectively. Although SCFA concentrations are relatively high, it must be remembered that the volume of the large bowel of both dogs and cats is small. Other fermentative end products include hydrogen sulfide, methane, ammonia, branched-chain fatty acids, amines, phenols, and indoles. The relative proportion of these compounds is influenced by colonic microflora composition, metabolic interactions among bacteria, nutrients available for fermentation, intestinal transit time, and a variety of host factors including age, immune status, and genetic makeup (Cummings and Macfarlane, 1991). The pH of the colonic contents and the resulting feces undoubtedly is affected by these factors, and a range of values from 5.5 to 7.5 might be expected, as reported in other species (Younes et al., 1995).

Short-chain fatty acids provide energy to the large intestinal cells. Roediger (1980) found that butyrate not only was utilized by the human intestine but also was the preferred energy source for colonocytes. These results were confirmed in dogs by Drackley et al. (1998) who found that isolated canine colonocytes oxidized butyrate at a rate 4.5 times greater than glucose. These studies implicate butyrate as a major fuel for the intestinal epithelium. The absorption of ammonia aids in the conservation of the endogenous nitrogen released into the digestive tract as a component of digestive enzymes and urea (see Figure 8.5 in Stevens and Hume, 1995).

Resident bacteria also influence mucosal structure and function (Buddington et al., 2000). The production of SCFAs as a result of fermentation of nutrients and endogenous secretions stimulates the absorption of water and electrolytes and, therefore, is involved with the osmoregulatory function of the gut. Absorption of SCFAs also increases the rate of sodium absorption, and the combined absorption of SCFAs and sodium from the large intestine accounts for much of the absorption of water (Stevens and Hume, 1995).

Furthermore, SCFAs stimulate the proliferation of enterocytes and colonocytes. The presence of SCFAs triggers the secretion of glucagon-like peptide 2, which stimulates mucosal growth and the expression of genes coding for some nutrient transporters in the ileum and, by so doing, enhances digestive function. Also, mucosal growth stimulated by SCFAs enhances barrier functions and decreases bacterial translocation. Butyrate is considered to be the most important SCFA with respect to the mucosa, whereas propionate is the least important. Therefore, the impact of bacterial fermentation on the gut is dependent on the relative proportions of different SCFAs produced.

A symbiotic relationship appears to exist between the adherent bacteria and the mucosa (Buddington et al., 2000). Adherent bacteria influence the endocytic and intracellular hydrolytic capacities of the mucosa and, by doing so, play a role in the degradation of potential antigens present in the lumen of the gut. This is important for regulation of the enteric immune system because it decreases the antigenicity of numerous macromolecules present in the gut. As a result, there is less potential for inflammation, which is counter to normal gut function. Adherent bacteria also act to increase production of secretory immunoglobulin A.

HORMONAL ASPECTS OF DIGESTION

In addition to digestive functions, the intestine and associated organs represent the largest endocrine organ in the body, and several endocrine cell types have been identified in the intestines of dogs (Tange, 1983) and cats (Kitamura et al., 1982). In other species, hormones originating from the gastrointestinal tract have proven to be critical for regulating digestive processes and whole-body metabolism (Buddington, 1996). Gastrointestinal hormones important to mammalian metabolism are listed in Table 1-1 along with information specifically related to dog and cat digestive physiology. Further information can be found on this topic in Stevens and Hume (1995). To date, very little is known about the impact of nutrition on the endocrine and immune functions of the dog and cat intestine.

MEASUREMENT OF, AND FACTORS AFFECTING, DIGESTIBILITY

Nutrient digestibility values provide information on the relative amounts of nutrients in the diet that can be used for productive purposes and, additionally, serve as an index of overall quality of the ingredients of dog and cat diets (Shields, 1993). The Association of American Feed Control Officials (AAFCO) publishes protocols for measuring dietary metabolizable energy content of dog and cat foods that have become standards for nutrient digestibility measurement because stool collection and protein digestibility measurement are necessary for both procedures (AAFCO, 2003). Dry matter and protein digestibility values are used to ensure maintenance of ingredient quality in the nutrition assurance programs developed separately by petfood manufacturers in the United States and Canada to ensure petfood nutritional quality through animal testing (Shields, 1993).

Accurate quantification of the amount of nutrient consumed by the animal and that excreted in the stool is needed for calculation of nutrient digestibility. The difference between these two quantities, divided by the amount consumed, represents the quantity digested. This is an "apparent" rather than a "true" figure because some of the nutrients absorbed from the intestinal tract come back into the gut, and feces contain a variable quantity of nutrients of nondietary origin (e.g., spent enzymes, pancreatic and gallbladder secretions, sloughed intestinal mucosal cells, bacteria). To quantify small intestinal digestibility, various methods involving surgical modification of the ileum have been used for both dogs and cats. Ileal contents may be collected before nutrients can be modified by large intestinal microbes. Ileal digestibility coefficients should be considered apparent rather than true values since endogenous secretions are part of the ileal chyme. Attempts have been made to estimate endogenous secretions when animals have been food deprived for a time, when a nitrogen-free diet (or a low amount of a highly digestible protein [e.g., 5 percent casein]) is fed (for "true" protein and amino acid digestibility measurements), or when graded levels of a nutrient are fed with extrapolation to zero intake (Young et al., 1991).

AAFCO (2003) protocols for dogs and cats recommend a 5-day diet adaptation phase followed by a 5-day period of feces collection to ensure accurate digestibility measurements. Nott et al. (1994) found that a 4-day collection period following a 3-day adaptation was sufficient to measure apparent digestibilities in dogs. However, in the cat, this shorter period of collection was insufficient for accurate determination of digestibility. Cats exhibit more variable consumption and excretion patterns than do dogs. In digestibility studies of cats, it is not unusual to have days in which consumption drops or when no stool is voided. This can seriously impact digestibility measurements (Shields, 1993).

Shields (1993) identified a number of factors that affect nutrient digestibility. First, although it is well understood that ingredient sources and absolute nutrient concentrations can influence digestibility measurements, effects of food processing often are overlooked. Ingredient particle size reduction generally will improve digestibility, and therefore food utilization, but will result in lower throughput of food in the manufacturing process, higher production costs, and reduced flowability. Processing conditions in the preconditioning chamber, the pellet mill-extruder-retort process, or the drying oven could impact diet nutritive value. In addition, feeding management practices such as previous diet fed and amount of food offered also could influence digestibility values.

Second, animal factors must be considered when evaluating digestibility. These include breed, age, gender, activity level, and physiological state. With regard to effects of breed, Meyer et al. (1999) conducted digestion experiments for 10 different canine breeds with body weights ranging from 4.2 to 52.5 kg (four to nine dogs per breed). Dogs were fed a canned or dry commercial diet with a constant dry matter intake of 13 g per kilogram of body weight per day, except for Irish wolfhounds which ingested only 10 g of dry matter per kilogram of body weight per day of the canned diet. The larger breeds tended to have higher fecal moisture content, less favorable fecal quality, and increased numbers of defecations. Irish wolfhounds, the largest breed tested, had feces with less moisture content than Labrador retrievers, indicating that body weight was not the only factor that should be considered. There were only small differences in apparent nutrient digestibilities among breeds. James and McCay (1950) and Kendall et al. (1983) found similar digestibility coefficients in medium-sized (Saluki, German shepherd, basset hound) and small dogs (dachshund, Cairn terrier, beagle). In both studies, the body weights of the experimental breeds may have been too similar to demonstrate small differences in digestive capacity. This is a critical point since Kirkwood (1985) and Meyer et al. (1993) found a relative decrease in weight of the gastrointestinal tract with increasing body weight of the dog. The weight of the

TABLE 1-1 Gastrointestinal Hormone Characteristics of Dogs and Cats

Hormone	Cell Type	Location of Action	Primary Action	Stimulus for Secretion	Data Collected with Dogs and Cats	Reference
Bombesin/ bombesin-like peptides (gastrin-releasing peptide [GRP], GRP-10, neuromedin [NMB])		Gastric fundus, antrum, duodenum, jejunum, and ileum	Stimulates: • Gastric acid secretion by modulating gastrin release (activates G cells via a Ca^{++}-dependent mechanism) • Cholecystokinin (CCK) release and pancreatic enzyme secretion • Gallbladder emptying, due either to bombesin itself or to CCK Inhibits: gastric emptying		*Dog:* bombesin stimulated neurotensin dog secretion	Barber et al., 1986
					Cat: bombesin increased lower esophageal sphincter (LES) pressure, mediated by substance P	Reynolds et al., 1986
					Cat: bombesin decreased food intake	Bado et al., 1989
					Cat: bombesin-like peptides contract terminal ileum via GRP receptors	Kortezova et al., 1994
					Cat: GRP-10 and NMB evoked contractions of esophagus, fundus, and duodenum	Milusheva et al., 1998
Gastrin	Type G	Gastric antrum, duodenum	Stimulates: • Secretion of gastric acid, pepsinogen, and glucagon • Proliferation of gut mucosa • Pancreatic HCO_3 production and pancreatic flow (weak) • Pancreatic enzyme secretion (strong) • LES pressure Inhibits: gastric emptying	Peptides and amino acids (AAs) in stomach; distention of stomach	*Dog and cat:* antral, duodenal, and jejunal mucosa contained same concentrations and molecular forms of gastrin in dog and cat	Rehfield and Uvnas-Wallensten, 1978
					Dog: gastrin stimulated LES pressure	Iwai et al., 1985
					Dog: determined that gastrin plays a role in the stimulation of pancreatic secretion after a meal	Johnson et al., 1987
					Dog: gastrin is of major importance in gastric acid stimulation caused by distention of the stomach by nutrients	Kovacs et al., 1989
					Cat: gastrin stimulates gastric acid secretion	Fernstrom et al., 1986, 1987
					Cat: along with CCK, gastrin plays a role in postprandial pancreatic secretion	Konturek et al., 1991
Cholecystokinin — formerly known as cholecystokinin-pancreozymin (CCK-PZ)	Type I	Duodenum, jejunum	Stimulates: • Pancreatic enzyme secretion • Gallbladder contraction Inhibits: • Gastric emptying and secretion (possibly mediated by nitric oxide) • Relaxes sphincter of Oddi	Peptides, AAs, and fatty acids (FAs) in duodenum	*Dog:* inhibition of gastric acid secretion by CCK is mediated, in part, by somatostatin	Konturek et al., 1992
					Dog: canine parietal cell CCK_B receptor has a single AA substitution at position 349 of the human CCK_B/gastrin receptor	Beinborn et al., 1993
					Dog: CCK induced both excitatory (due to acetylcholine) and inhibitory (due to nitric oxide) actions in intestine and excitatory action of antrum	Vergara et al., 1996
					Dog: CCK was a potent and specific pancreatic vasodilator, playing an important role in the regulation of the intestinal phase of pancreatic circulation	Nakajima et al., 2001
					Cat: diets that cause taurine depletion have lower protein digestibilities and cause greater CCK secretion than diets that maintain body taurine status	Backus et al., 1995a
					Cat: although cats are strict carnivores, they secrete CCK in response to intact proteins and free AAs similar to humans	Backus et al., 1995b
					Cat: intact proteins result in greater CCK secretion than free AAs	Backus et al., 1997

TABLE 1-1 continued

Hormone	Cell Type	Location of Action	Primary Action	Stimulus for Secretion	Data Collected with Dogs and Cats	Reference
Secretin	Type S	Duodenum, jejunum	Stimulates: • Pancreatic HCO_3 synthesis and secretion • Release of bile Inhibits: • Gastric motility and secretion • LES pressure • Net water absorption in gallbladder	Acidic chyme and FAs in duodenum and jejunum	*Dog:* secretin increased somatostatin release; secretin decreased gastric acid production by modulating histamine release *Cat:* secretin increased biliary and pancreatic secretions	Gerber and Payne, 1996 Jansson et al., 1978a
Gastric inhibitory peptide (GIP)	Type K	Duodenum, jejunum, and ileum (mainly jejunum)	Stimulates: Insulin secretion and synthesis—main "incretin" factor Inhibits: • Gastric acid secretion • Gastric and small intestinal motility	Glucose, AAs, and FAs in small intestine, with FAs being the most potent; somatostatin regulates release	*Dog:* GIP stimulated secretion from jejunum and ileum with little change to electrolyte concentrations *Dog:* GIP suppressed the stimulatory effects of motilin on the duodenum, but had no effects on spike potentials produced by CCK-octapeptide *Dog:* jejunum has 69% of intestinal K cells *Cat:* decreases LES pressure	Barbezat and Grossman, 1971 Castresana et al., 1978 Damholt et al., 1999 Sinar et al., 1978
Glucagon-like peptide 1 (GLP-1)—part of enteroglucagon measured in early experiments	Type L	Duodenum, jejunum, and ileum (mainly jejunum)	Stimulates: • Insulin secretion—"incretin" factor • Part of "ileal brake" Inhibits: • Gastric acid secretion and motility • Pancreatic enzyme secretion • Appetite and food intake	FAs in duodenum; release mediated, in part, by CCK; GIP stimulates release; somatostatin regulates release	*Dog:* CCK is not an incretin in the dog, but GLP-1 is the major incretin during euglycemia; both GIP and GLP-1 may be incretins during hyperglycemia *Dog:* GLP-1 may participate in "ileal brake" *Dog:* increase in GLP-1 mediated, in part, by CCK *Dog:* jejunum has 51% of intestinal L cells; 30% found adjacent to K cells suggesting paracrine interaction between the cells	van der Burg et al., 1995 Wen et al., 1995 Fung et al., 1998 Damholt et al., 1999
Glucagon-like peptide 2 (GLP-2)—part of enteroglucagon measured in early experiments	Type L	Small intestine and colon	Stimulates: • Proliferation of gut mucosa • May be part of "ileal brake" Inhibits: • Gastric secretion and motility • Food intake	Ingestion of food, particularly carbohydrate and fat; SCFAs stimulate release; somatostatin regulates release; release may be mediated by GIP and GRP release		
Vasoactive intestinal polypeptide (VIP)	Type D_1, nerve cells and fibers	Gastric, small intestine, and colonic mucosa	Stimulates: • Blood flow through gut • HCO_3, electrolyte, and water secretion from pancreas Inhibits: • Secretion of gastric acid, pepsin, and intrinsic factor	Acetylcholine stimulates release	*Dog:* VIP inhibited gallbladder contraction stimulated by neurotensin and CCK *Dog:* acetylcholine evoked release of VIP from VIP-containing neurons in dog ileum *Cat:* VIP relaxed gallbladder and induced a net fluid secretion into lumen *Cat:* VIP antagonized responses to excitatory neuropeptides (bombesin, substance P, and CCK) in gastric smooth muscle	Milenov et al., 1993 Kimura et al., 1994 Jansson et al., 1978b Merlo and Cohen, 1989

			• LES pressure • Gastric motor function • Net water absorption in gallbladder • Relaxant effect of VIP amplified by nitric oxide		*Cat:* VIP inhibited basal LES tone	Parkman and Reynolds, 1990
Motilin	Type EC_2	Duodenum, jejunum	Stimulates: • Motor activity of gut through release of acetylcholine, opiates, and serotonin • LES pressure • Regulation of migrating motor complex (MMC) activity		*Dog:* canine motilin has AA differences in 5 positions compared with porcine motilin *Dog:* motilin decreased VIP output *Dog:* motilin stimulates release of opiates which, in turn, inhibit VIP release *Dog:* acetylcholine is a major regulator of motilin release *Dog:* exogenous motilin stimulated insulin release *Dog:* motilin receptors may exist in dog colon as well as small intestine *Cat:* sequence homology between cat and porcine/human motilin was 81.8% *Cat:* gastric corpus and antrum, duodenum, jejunum, and ileum have motilin receptors	Poitras et al., 1983 Manaka et al., 1989 Fox-Threkeld et al., 1991 Poitras et al., 1993 Suzuki et al., 1998 Chiba et al., 2000 Depoortere et al., 1993a Depoortere et al., 1993b
Somatostatin	Type D, nerve cells and fibers	Stomach, small intestine, and pancreas	Inhibits: secretion of other enteroendocrine peptides	Fat and protein	*Dog:* somatostatin inhibited gallbladder contraction stimulated by neurotensin and CCK *Dog:* somatostatin inhibited gastrin and histamine secretion in antrum *Dog:* somatostatin inhibited pancreatic polypeptide and peptide YY release *Cat:* somatostatin selectively inhibited bombesin-induced, but not substance P-induced, LES contraction	Milenov et al., 1993 Zaki et al., 1996 Gomez et al., 1997 Parkman and Reynolds, 1990
Pancreatic polypeptide (PP)	Type PP	Pancreas	Inhibits: pancreatic protein and HCO_3 secretion	Protein; bombesin, CCK, and neurotensin stimulate secretion	*Dog:* CCK stimulated PP release and enhanced PP released originating from other stimuli	Jansen et al., 1990
Substance P	Type EC, nerve cells and fibers	Widely distributed throughout gut mucosa and nerves	Stimulates: • Neuronal activity • Pepsinogen release • LES contraction • Ileocecal sphincter contraction • May cause release of serotonin • Regulation of pancreatic enzyme secretion • Regulation of intestinal peristalsis	Hyperosmolarity and acid	*Dog:* canine chief cells possess substance P receptors and stimulate pepsinogen release *Cat:* substance P evenly distributed along gut, unlike humans, rats, and pigs that have distinct regional differences *Cat:* vagal stimulation released substance P from duodenum and jejunum, but not distal ileum; substance P not detected in feline EC cells *Cat:* substance P and serotonin released independent of one another suggesting different intestinal sources; authors suggest substance P released from neurons rather than EC cells	Vigna et al., 1989 Holzer et al., 1982 Grønstad et al., 1985 Grønstad et al., 1987

TABLE 1-1 continued

Hormone	Cell Type	Location of Action	Primary Action	Stimulus for Secretion	Data Collected with Dogs and Cats	Reference
Neurotensin	Type N	Central nervous system, small intestine, and large intestine (predominantly in the distal ileum)	Stimulates: • Vasodilation and blood flow • Proliferation of gut mucosa • Gallbladder pressure and contraction • Pancreatic secretion • Conjugated bile acid reabsorption in distal small intestine Inhibits: • Gastric secretion and emptying • LES pressure • May have an inhibitory or excitatory action on gut motility depending on dose, organ, and species	Many food components, particularly FAs	*Dog:* in contrast to earlier findings, neurotensin stimulated gastric acid secretion in response to protein in the stomach *Cat:* neurotensin produced a contractile response at distal ileum, ileocecal sphincter, and proximal colon, but also had inhibitory effects on these areas	Eysselein et al., 1990 Rothstein and Ouyang, 1989
Serotonin (5-hydroxytryptamine; 5-HT)	Type EC and nerve cells	Small and large intestine	Stimulates: • Neuronal activity • Gut motility • Vasodilation	Acidic pH, hypertonic solutions, neural stimulation (vagus nerve)	*Dog:* contractility from motilin mediated through serotonin *Cat:* serotonin had excitatory and inhibitory effects on ileum and ileocecal sphincter, depending on dose administered *Cat:* vagal nerve stimulation increased serotonin release in duodenum and jejunum, but not in distal ileum	Kellum et al., 1986 Ouyang and Cohen, 1983 Grønstad et al., 1985
Enkephalins		Stomach, duodenum, and gall bladder	Inhibits: • Electrical activity of neuronal cell body • Acid-stimulated pancreatic secretion and secretin release (appears to be mediated by somatostatin)		*Dog:* methionine enkephalin (MEK) inhibited pancreatic exocrine secretion *Dog:* MEK reduced VIP output	Chey et al., 1980 Manaka et al., 1989
Peptide YY (PYY)	Type L	Ileum, colon	Stimulates: • Proliferation of gut mucosa • Small intestinal absorption • Part of "ileal brake" Inhibits: • Gastric emptying and fasting motility of stomach • Gastric, biliary, and pancreatic secretions	Presence of fat in duodenum; gastric acid secretion; release mediated by CCK	*Dog:* decrease in pancreatic secretions by PYY is mediated, in part, by a decreased CCK release *Dog:* PYY participates in the ileal brake *Dog:* PYY release and mRNA expression up-regulated by gastric acid secretion, but down-regulated by circulating gastrin *Dog:* fat-induced ileal brake depends on PYY *Dog:* PYY was increased by presence of fat in duodenum and increased by CCKA receptor activation *Dog:* PYY antagonist did not alter gastric acid secretion or gastric emptying, which calls into question its role in these functions	Lluis et al., 1988 Wen et al., 1995 Gomez et al., 1996 Lin et al., 1996 Fung et al., 1998 Zhao et al., 1999

empty intestinal tract in small breeds is 6 to 7 percent of their body weight, and it decreases to 3 to 4 percent in large and giant breed dogs. Weber et al. (2003) evaluated the effects of age and body size on the apparent digestibility of a dry expanded diet. Breeds of dogs used were miniature poodles, medium schnauzers, giant schnauzers, and Great Danes. Digestibility experiments were conducted at 11, 21, 35, and 60 weeks of age. Nutrient digestibilities were significantly higher in large dogs at all ages studied, even though these dogs had lower fecal scores and increased fecal moisture concentrations.

Age, too, is a factor impacting nutrient digestibility. In the study of Weber et al. (2003) cited above, macronutrient digestibilities increased significantly with age (from 11 to 60 weeks) for all four dog breeds used in their study. Shields (1993) reported on a study conducted with Brittany spaniel puppies, which suggested that digestibility values obtained using 11-week-old puppies for dry matter, protein, and energy were 1, 5, and 3 percent lower, respectively, than those obtained with adult dogs ranging from 2 to 4 years of age. Between 6 months and 2 years of age, however, no differences were found. Whether the lower digestibility values for puppies resulted solely from increased food consumption (relative to body weight or intestinal length) or whether digestive efficiency is lower for this age group is unclear.

Buffington et al. (1989) compared digestive efficiency in beagles from 2 to 17 years of age, and results suggested that at least up to 10 years of age, no digestibility reductions were noted. At 15 to 17 years of age, minor reductions in digestibility measurements were observed. Harper and Turner (2000) conducted a 24-week study to evaluate the effect of age on apparent digestibility in weaned, growing kittens fed two diets (one wet, the other dry), both capable of maintaining kitten growth. Mean apparent digestibilities of dry matter, organic matter, protein, and carbohydrate were lower in kittens younger than 19 weeks of age, suggesting that more immature kittens are less able to digest solid food. There were no significant interactions between diet and age. Also, there were no significant differences between the growth rates supported by the two diets despite differences in their carbohydrate and fat contents. Fat was the only nutrient whose mean apparent digestibility increased with age up to 24 weeks. Bile salt-activated lipase is a component of cat milk, and evidence suggests that it plays a role in the fat digestion process in the suckling kitten. There are no reports of pancreatic lipase development in the cat, but the presence of bile salt-activated lipase in cat milk and reports of low fat digestibility in the kitten at weaning indicate that lipase development may be slow in the cat. Alternatively, the cat may display a similar type of lipolytic enzyme development to the pig, a nonparallel pattern suggested to reflect the importance of the different enzymes at the suckling and postweaning phases (Jensen et al., 1997). Other enzymes impacted by age include lactase and amylase. Lactase activity was highest in the intestine of young dogs (5 days old) and decreased to levels found in adults by 29-61 days of life (Welsh and Walker, 1965). Kienzle (1988) found amylase activity in pancreatic tissue of puppies to be lower (7.1 ± 4.3; 251.5 ± 108.2; 2,098.0 ± 1,073; and 1,623.0 ± 1,431 $U \cdot g^{-1}$ wet weight at 4, 8, and 12-16 weeks of age, and 8-10 months of age, respectively) than for dogs over 2 years old (4,665.0 ± 781 $U \cdot g^{-1}$ wet weight). This indicates an age-related ability of the dog to digest starch.

Little research exists with regard to gender effects on digestibility. The limited information available suggests that food intake and fecal output are higher, and nutrient digestibility lower, for males of both species compared to females, with a suggestion that gender differences are greater for cats than for dogs (Shields, 1993).

Third, housing and environmental factors could impact nutrient digestibility, but research with dogs housed in metabolism cages or covered kennel runs indicated that digestibility values were similar, regardless of housing system used (Shields, 1993). "Effective" environmental temperature, which comprises air temperature, humidity, air velocity, flooring material, wall-ceiling insulation, and temperature acclimation and their interactive effects, also might have an effect on nutrient digestibility values. Temperature can exert its effect through either compensatory metabolic mechanisms to maintain body temperature or absolute amount of food consumed. Other environmental factors such as the caretaker-animal relationship and photoperiod likely influence nutrient digestibility, although these effects are difficult to quantify (Shields, 1993).

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2

Feeding Behavior of Dogs and Cats

FOOD INGESTION BY FERAL DOGS AND CATS

At the present stage in the domestication of dogs and cats, it is difficult to assess with certainty a complete description of the normal feeding behavior of either. In different ways, both have become dependent on humans for their food supply. Some information can be gained by observing feral dogs and cats or other Canids and Felids; however, much of our information still comes from the laboratory setting. From field studies, it is apparent that there are many differences in feeding behavior between dogs and cats. Canids in general, including dogs, hunt in packs, but have broad feeding habits, which include berries, other fruit, and various parts of plants as well as both small and large prey. On the other hand, Felids in general (except the lion), including the domestic cat, are solitary hunters, showing no omnivorous feeding behavior whether feral or simply house cats allowed outside; thus, felids are considered strict carnivores (Ewer, 1973). When out hunting, domestic cats seek small prey such as mice, birds, lizards and insects such as grasshoppers (McMurry and Sperry, 1941; Eberhard, 1954; Coman and Brunner, 1972; Fitzgerald, 1988; Robertson, 1998) and limit the size of their prey to occasionally killing and eating adult rabbits. It is interesting that house cats search out wild prey more often when meat is not in their diet (Robertson, 1998). Feral dogs, on the other hand, prefer hunting in packs and hunt medium-sized to large prey, including deer, caribou, and even humans (Avis, 1999).

Since a mouse or small bird provides about 30 kcal of metabolizable energy (ME), a cat must catch 8-12 of these animals every 24 hours to provide its energy need. Any dog owner, on the other hand, knows that his or her dog can eat its 24-hour energy need in just a few minutes in a single meal. It has been reported that a male Labrador once ate 10 percent of its body weight of a canned dog food (Mugford, 1977) and a wolf deprived of food for 7 days is known to have eaten 17 percent of it body weight of meat (Young, 1944).

DIURNAL RHYTHMS, AND FEEDING AND DRINKING PATTERNS

Free-feeding patterns of dogs and cats in the laboratory where food is available continuously confirm that dogs eat fewer, larger, and more variable-sized meals than cats (Mugford, 1977; Mugford and Thorne, 1980). Cats voluntarily eat 12-20 meals per day evenly spread between the light and dark periods (Mugford and Thorne, 1980; Kane et al., 1981b), whereas dogs, depending upon breed, will eat four to eight or even more meals (Mugford and Thorne, 1980), generally eaten during the light period, with some breeds also eating during the dark period. Kane et al. (1981b) reported that, after adaptation to each diet for a week or more, adult cats ate the same size (in kilocalories of ME) and number of meals whether they were fed commercial dry or canned or laboratory-prepared amino acid or protein purified diets. In their studies, the mean meal size was about 15-30 kcal ME, with the cats eating about 12-20 meals per day (means, 15.7-17.4).

Although fresh water is always recommended for both dogs and cats, the amount required varies greatly with type of diet and environmental conditions. Dogs will spontaneously drink more water per kilogram of body weight than cats (Anderson, 1981), which is thought to be the result of the cat evolving as a desert animal (Chew, 1965). Cats can concentrate urine more than either dogs or humans and can rehydrate drinking seawater (Wolf, 1959). Cats are slower to initiate drinking or to drink enough for complete rehydration than dogs who, when dehydrated, will drink enough to replenish 6 percent of their body weight in an hour compared to the 24 hours that it takes for cats (Adolph, 1947). This weak thirst drive of cats results in an intake of only about 2 mL of water for every gram of dry food ingested and an increased risk of urolith formation as compared to cats fed food containing more water, such as a canned food containing 78-82 percent water. Nevertheless, both dogs and cats are able to maintain water balance when fed meat or fish

containing 67-73 percent water, without drinking any water (Caldwell, 1931; Danowski et al., 1944; Prentiss et al., 1959). However, even cats could not maintain water balance with meat desiccated to a moisture content of 61 percent (Prentiss et al., 1959), possibly because of the volume of urine required to excrete urea. The ratio of 2 mL water per gram of dry matter (DM) is similar to that of prey, and it is interesting that when water intake has been measured in the laboratory setting in cats fed canned food (Kane et al., 1981b), within 2 days the cats stop drinking; indeed, it could be considered that the water ingested by cats eating canned foods causes diuresis in cats. Diuresis, as in other animals, can be caused by additional sodium in the diet, but it takes 2-4 percent sodium chloride to increase water intake in cats (Anderson, 1982). Thus, because of possible adverse effects of high sodium intake, addition of water to food is the most common way to increase water intake (Anderson, 1982), even to help prevent uroliths (Hamar, 1976). Dogs drink primarily during the day unless they are dehydrated, whereas cats drink during both the light and the dark periods (Kane et al., 1981b). Unless dogs and cats were meal-fed (one to two meals per day), there were no correlations between eating and drinking patterns (Kanarek, 1975; Kane et al., 1981b), despite the fact that the number of drinking bouts approached the number of meals.

All animals live with diurnal cycles caused by the earth's rotation once each day. The most common diurnal cycle is the sleep-wake cycle, which contributes to a variety of biological rhythms. Circadian rhythms are free-running rhythms of about 24 hours that are synchronized by the light-dark cycles of day and night but, even in constant light or constant darkness, continue as a result of an innate circadian oscillator present in most mammals in the suprachiasmatic nucleus (SCN). Thus, in most animals, the sleep-wake cycle is a circadian rhythm. In this sense, it was reported long ago that cats do not have clear-cut circadian rhythms (Szymanski, 1919, as cited by Randall et al., 1985). For example, core body temperature is normally circadian in most mammals, but not in cats (Sterman et al., 1965). Neither dogs nor cats have clearly defined circadian rhythms (Hawking et al., 1971); both have irregular patterns throughout the day and night. The effect of this on the behavior of cats is readily apparent when we realize that cats, for example, as compared to chickens or rats, are both diurnal and nocturnal, hunting rodents at night and song birds during the day, sleeping in the day and sleeping at night, whining to come in and out of the house in both the daytime and the nighttime. Randall et al. (1985) reported a comprehensive study on the feeding behavior of cats and concluded that food intake at night was influenced (increased) by dim light (starlight) and by the presence of humans. They observed a wide range of individual activity and feeding patterns, with no circadian rhythms apparent in constant light; however, they did observe free-running circadian rhythms in constant darkness. Studies of farm cats (Macdonald and Apps, 1978) provide evidence that some cats are nocturnal—that is resting in the barns during the day and traveling out considerable distances at night. Minor disturbances, such as routine noises by humans, easily modify any existing rhythm. Kane et al. (1981b, 1987) examined feeding patterns in an undisturbed animal laboratory, using electronic balances and interrupting the cats only once a day during the light period. They found that the cats ate at random, during both the light and the dark cycles and that there was a trend toward eating a bit more during the light period, apparently because that is when they were disturbed and provided with fresh food. Although there were clear differences in palatabilities among the various diets used (commercial canned, commercial dry, purified amino acid diet, purified protein diet, high-fat diet, low-fat diet), after adaptation to each diet for a few days, cats ate from 12 to 20 meals per day consisting of 15-30 kcal ME per meal. Mugford and Thorne (1980), studying a variety of commercial pet foods, also found that the cats ate many meals during both the light and the dark periods. Although not entirely uncommon, it appears against the natural feeding behavior of cats to be forced to eat only once a day, whereas most dogs thrive on a regimen of eating once a day.

ROLE OF IMPRINTING AND SOCIAL FACTORS ON FEEDING BEHAVIOR

When feeding dogs and cats, it is important to remember that both early feeding experiences and recent experiences can influence their dietary choice. In a number of species, including dogs and cats, exposure to specific dietary flavors and textures early in life can enhance preferences later in life. The classic work of Kuo (1967) shows that pups, when fed only a single, unique-flavored diet (e.g., soybean-based diet) for 6 months, would eat no novel foods, whereas pups fed a mixed diet would eat any new food that was presented. Cats are notorious for getting "fixed" on one particular flavor if fed only that flavor for a long period of time, whereas, if the diet is varied, they never seem to select only one type or one flavor of diet. However, Mugford (1977) has reported that well-adjusted normal adult dogs and cats will select new flavors rather than the one they were fed (normal commercial foods) as puppies or kittens. Dogs and cats fed a variety of diets are known to be normally neophilic; that is, after feeding on only one flavor for a time, they will select a new flavor. This rejection of the familiar flavor has often been referred to as the diet becoming "monotonous," or as flavor "fatigue," and is common in any species that is well socialized and comfortable in its surroundings. If the same dogs and cats are placed in a strange environment or stressed in some other way, then the animals become neophobic—that is, they avoid any new flavor and select one that is familiar (Bradshaw and Thorne, 1992). The degree of these responses is not hard and fast but is modified by the palatability of the foods. Therefore, the palatability and novelty of

any particular food and the level of hunger and stress for dogs and cats are all important in acceptance and choice of any particular food at any particular time. Naive cats offered new diets will generally select gel (moist) diets over dry diets; however, some animals will select familiar dry commercial diets over unfamiliar canned diets. Cats prefer warm food to cold or hot food (Bradshaw and Thorne, 1992). Thus, it is important to warm food that is kept in a refrigerator and, when changing diets, to do so gradually by mixing part of the familiar diet with the new diet a few times before switching completely.

DIETARY CHOICE, PALATABILITY, LEARNED TASTE AVERSIONS, AND PREFERENCES

According to Webster's dictionary, palatability is being agreeable to the taste and hence, savory and pleasing—that is, a hedonic response of an organism to a foodstuff. This is a very general definition and is not sufficiently analytical to use in a scientific way involving both pre-absorptive and post-absorptive behavioral responses to food in situations that involve learned taste aversions or sensory-specific satiety. In observing animals, they select, avoid, or have no preference when given a choice between two diets, and although there are indications of joy or happiness by dogs and cats, hedonic feeding responses cannot be evaluated readily. As indicated in an extensive discussion by nutritional biochemists, physiological psychologists, and sensory physiologists (Appetite, 1990), the meaning of the term palatability has become confused. For example, a given flavor (odor, taste, texture, temperature) that is highly acceptable when offered to naive dogs or cats may be completely rejected when used with a diet that has previously caused a learned taste aversion. Therefore, although the term palatability is used extensively in describing the eagerness of dogs and cats to ingest various foods—especially by the petfood industry—it is not very useful and probably should be avoided in scientific articles. One definition of palatability is that it "refers to the physical and chemical properties of the diet which are associated with promoting or suppressing feeding behavior during the pre-absorptive or immediate post-absorptive period, i.e., an unconditioned response, before a metabolic and any subsequent conditioning effect on food intake occur" (McArthur et al., 1993). Although quite precise and useful for experimental purposes, this definition of palatability requires the use of naive animals in a specific feeding situation, which is not always feasible. Nevertheless, this definition of palatability is used in this chapter.

Rats are the species "par excellence" when it comes to studying the effect of nutrient deficiency and excess on dietary choice; thus, comparisons with the rat are made in describing the dietary choice of dogs and cats. For example, rats, when deficient in threonine or lysine, will avoid the diet that has the lesser content by only 0.01 g per 100 g diet; that is, rats will choose a diet that contains 0.200 g of threonine per 100 g of diet over one that contains 0.191 g of threonine per 100 g (Hrupka et al., 1997). Also, in choosing between two diets, rats will also avoid the diet that has less lysine, even if no difference in weight gain is apparent between the two dietary levels of lysine (Hrupka et al., 1999). Equivalent dietary choice studies have not been done in dogs and cats. It is clear, however, that dogs are more like rats than cats are. When offered various levels of dietary protein choices, both rats (Musten et al., 1974; Leung and Rogers, 1981; Peters and Harper, 1984) and dogs (Romsos and Ferguson, 1983; Torres et al., 2003) will choose about 25-30 percent of their calories as protein, depending on the type of protein, quantity of sugar in each diet, and level of protein previously fed, whereas cats will not avoid protein-free diets in favor of low-protein or adequate-protein diets (Cook et al., 1985, 1996). Thus, compared to nutritional adequacy, positive palatability factors such as amino acids, peptides, and texture have a greater effect on cats than on dogs. More than 30 years ago, Rozin and Kalat (1971) reviewed the nature of the learning process that is now called "learned taste aversion" and distinguished it from cognitive learning. It is clear now that many of the earlier choices for adequate over inadequate diets were the result of learned taste aversions. This has led to the concept that most animals learn what not to eat (via learned taste aversions) rather than what to eat (learned taste preferences). Most of these early studies, and those in the current literature, were done on omnivores or herbivores. Omnivores or herbivores avoid a wide variety of deficiencies including deficiencies of protein (Musten et al., 1974; Leung et al., 1981); essential amino acids (Leung and Rogers, 1987) (e.g., threonine); many, but not all, B vitamins (e.g., thiamin, riboflavin; Scott and Verney, 1947; Rozin, 1965); several macrominerals (e.g., calcium, phosphate, sodium, potassium; Scott et al., 1950; Nachman, 1962; Holcombe et al., 1976; Taher et al., 1984) and at least one micromineral (zinc; Christensen et al., 1974). Both dogs and cats have been shown to develop learned taste aversions (Mugford, 1977); however, so little work has been done with feeding behavior and nutrient deficiencies in either dogs or cats that their responses cannot be generalized.

It appears that arginine deficiency-induced hyperammonemia results in learned taste aversions in most species, including dogs and cats (Morris and Rogers, 1978; Burns et al., 1981; Rogers, 1994), whereas, as mentioned earlier, cats do not appear to develop a learned taste aversion to a protein-free or low-protein diet (Cook et al., 1985, 1996), nor do they select sodium even if they are sodium deficient (Yu et al., 1997). Although the dog is "anatomically" a carnivore, metabolically it has many characteristics of omnivores such as the conversion of carotene to vitamin A, tryptophan to niacin, cysteine to taurine, linoleate to arachidonate, and other metabolic differences, which result in different nutrient requirements for dogs and cats both qualitatively and quantitatively. It would appear that most of

the differences in dietary choice between rats and cats are the result of the lack of metabolic pressure during evolution for selection by cats since cats are strict carnivores and, if eating animal tissue, would never have had to make such a choice to maintain homeostasis. Dogs, however, exhibit some of the metabolic characteristics of both omnivores and strict carnivores. As mentioned above, dogs clearly select for protein whereas cats do not. No work has reported whether dogs or cats exhibit learned taste aversions to the various vitamins and mineral deficiencies. As mentioned earlier, dogs appear to be more similar to rats than cats are; thus, metabolically and by nutrient choice, dogs should be considered omnivores. It is interesting that cats develop a learned taste aversion to a diet that causes metabolic acidosis, even if it results from the protein component of the diet (Cook et al., 1996). Thus, cats will avoid lower-sodium diets to avoid metabolic acidosis but not to prevent a sodium deficiency when metabolic acidosis is not present (Yu et al., 1997).

As noted earlier, cats will become fixed on a single food if allowed to eat only one food for a long period of time (Kuo, 1967; Mugford, 1977; Mugford and Thorne, 1980; Kane, 1989). This has the appearance of a learned taste aversion, but there is no evidence that this phenomenon is caused by any nutrient deficiency. In fact, cats are normally neophilic (selecting a new food or new food flavor) if fed a variety of foods and flavors throughout their lives (Mugford and Thorne, 1980). It is known to be easier to get young kittens than older cats to eat poorly palatable foods (e.g., purified diets). Texture and moisture content, although important to both dogs and cats, are clearly more important for cats (Kane, 1989). Cats normally select a moist diet (meat or canned diet) over a dry pelleted or expanded diet; however, some cats that have had a dry commercial diet for a long period of time will select the dry expanded diet. However in contrast to dogs, cats will not eat a powdered (ground expanded commercial or powdered purified) diet but will eat the same diet if it is pelleted or provided as a mash or gel form. Generally, the gel form is the type most often selected. Flavors that enhance the acceptance of diets by both dogs and cats include animal fat (Kane, 1981a), peptides, and certain amino acids (White and Boudreau, 1975; Beauchamp et al, 1977). Sugar enhances the acceptance of diets by dogs (Torres et al., 2003) but not by cats (Beauchamp et al., 1977). Medium-chain fatty acids per se or in triglycerides have a negative palatability for cats (MacDonald et al., 1985). As little as 5 percent medium-chain triglycerides or 0.1 percent caprylic acid resulted in an immediate avoidance the first time cats had an opportunity to select between these diets and a diet containing hydrogenated beef tallow as the fat source. Cats would not eat enough diet to maintain their weight when hydrogenated coconut oil was provided at 25 percent of the diet (MacDonald et al., 1985). Dogs, on the other hand, readily eat meat and other foods that are rather rancid. It is known that cats are more sensitive to bitter taste than several other species (Carpenter, 1956); for example, cats first avoid a quinine solution at 5 $\mu mol \cdot L^{-1}$ whereas rabbits and hamsters first avoid quinine solution at 2,000 $\mu mol \cdot L^{-1}$. Dogs appear to be intermediate, strongly rejecting a quinine solution at about 300 $\mu mol \cdot L^{-1}$ (Grace and Russek, 1969). Saccharin (0.1 percent) is avoided by both dogs and cats (from electrophysiological evidence, because of the bitter taste). Nevertheless, even though dogs select 10 percent sucrose solution, cats will not select for or against any concentration of sucrose (Carpenter, 1956; Grace and Russek, 1969; Kitchell, 1978; Castonguay et al., 1987).

Dogs and cats especially like the flavor components in meat and peptides (protein hydrolysates or enzymatic digests) and free amino acids such as alanine, proline, lysine, histidine, and leucine (White and Boudreau, 1975; Beauchamp et al., 1977; Hargrove et al., 1994). Dogs appear to also respond very positively to the flavor of umami (monosodium glutamate plus 5′-nucleotides; Kumazawa and Kurihara, 1990).

CONTROL OF FOOD INTAKE

Although there are reports that cats do not regulate body weight, for example, by increasing food intake when a diet is diluted with celluflour or kaolin (Kanarek, 1975; Hirsch et al., 1978) or when additional calories are provided in water (Castonguay et al., 1987), it would appear that palatability and energy loss in the urine are the probable reasons for the lack of adjustment in these studies (Goggin et al., 1993). Most cats can be changed from canned to dry to purified diets without marked changes in energy intake or body weight (Kane et al., 1981b). It has long been known that dogs adjust their energy intake as the energy density of the diet is increased or decreased (Janowitz and Grossman, 1949); however, there is a limitation, even in dogs, as to how much cellulose (<10 percent) can be added without causing a decrease in energy intake (Jewell and Toll, 1996). As mentioned above, suppressing activity (keeping dogs or cats in small places) and feeding highly palatable, energy-dense diets for long periods of time contribute to obesity in dogs and cats just as in humans. Behaviorally, it is interesting that in cats (Adamec, 1976), predatory behavior takes precedence over eating since cats will stop eating a highly palatable diet to go kill a rat and then return to their food without eating the rat. This type of behavior probably contributes to the survival of strict carnivores.

FEEDING RECOMMENDATIONS

Clean, fresh water should be provided for both dogs and cats at all times. They should be fed a complete and balanced diet that fulfills their requirements as described in Chapter 15. There is generally much flexibility in deciding upon a feeding schedule. Many dogs and cats can be fed free-choice, and they will maintain their proper weight.

About 30-40 percent of dogs and cats will overeat and be overweight or even obese if allowed to eat as much as they want at all times during the day. Although growing puppies should be fed either free-choice or two or three times a day, normal adult dogs will maintain optimal health if fed only one meal a day. Cats, however, normally eat many meals a day; thus, it is not normal for them to eat only one meal a day, and most cats cannot adapt to such a dietary regimen. If the dog or cat is too heavy, it should be fed less food. This can be accomplished with any animal in a number of ways. The most obvious is to simply feed less using the same feeding regimen. Thus, for the dog, that could be one meal a day or feed the correct amount in two feedings, one in the morning and one in the evening. For the cat, it would be putting the right amount of food in the food bowl and allowing the cat all the time it wants to eat that amount. There are other approaches, such as feeding a less energy-dense diet, feeding a less palatable diet, allowing less time for feeding, and other regimens. Some of these regimens work for some animals, but not for all. Often, an even greater problem is preventing the animal from eating at the neighbors' or keeping the family from feeding treats or table scraps indiscriminately. If, on the other hand, a dog or cat is not eating enough (unusual unless it is sick) to maintain a normal weight, warming the food and adding water in the form of meat broth often helps.

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3

Energy

INTRODUCTION

Energy Evaluation and Requirements: Two Ways of Looking at the Issue

Energy is not itself a nutrient but is rather a property contributed to diets by the three nutrients: fats (lipids), carbohydrates, and proteins. Energy is expressed in either kilocalories (kcal) or kilojoules (kJ):1 kcal is equivalent to 4.184 kJ. In this report, kcal are used as this is the common expression for energy units used in the United States. Dogs and cats require energy for support of metabolism during maintenance, growth, reproduction, lactation, and physical activity. In the absence of adequate energy, animal performance will be suboptimal, and there will be depletion of energy and nutrient stores.

The gross energy (GE) in a food is defined as the total chemical energy arising from complete combustion of a food in a bomb calorimeter. The heat of combustion of a food can be predicted from chemical analysis using standard values for the nutrients. For crude fat, a range of 8.7-9.5 $kcal \cdot g^{-1}$ organic matter has been reported; a value of 9.4 $kcal \cdot g^{-1}$ fat is appropriate for petfoods. Heat of combustion increases with increasing chain length and decreases with increasing degree of desaturation. For fat in petfoods, which is often relatively long chained and partially desaturated, a GE in the upper part of this range seems justified (Kienzle et al., 2002). For crude protein, a range of 5.3-5.8 $kcal \cdot g^{-1}$ is described in the literature (Kienzle et al., 1999); in petfoods, 5.7 $kcal \cdot g^{-1}$ organic matter appears to be appropriate. Heat of combustion of carbohydrates, including non-starch polysaccharides (NSPs), ranges between 3.3 and 4.3 $kcal \cdot g^{-1}$ organic matter, and GE of lignin between 4.1 and 7.0 $kcal \cdot g^{-1}$ organic matter. Lignin is not a major compound of fiber in petfoods; therefore, the contribution of NFE (nitrogen-free extract; represents starch, sugar, and NSPs that become soluble when cooked in diluted alkalies and acids) and crude fiber can be assessed together sharing a GE of 4.1 $kcal \cdot g^{-1}$ organic matter (Kienzle et al., 2002).

The transformation of GE into net energy (NE) for maintenance, growth, reproduction, or activity can be described by three steps (Figure 3-1). The first step is digestibility of energy, and the second metabolizability of digestible energy (DE). Energy losses by urine and by fermentation gases are subtracted from DE to determine metabolizable energy (ME). Finally, in a third step, the heat loss during transformation of ME into NE is taken into account. The percentage of ME obtained as NE is defined as the efficiency of utilization.

Availability of energy is approached in two different ways: by energy evaluation of food or by energy requirement calculations for the animal. In energy evaluation of food, each step of energy transformation is considered individually for each food, whereas in requirement calculations, mean factors for respective steps of transformation (such as the utilization of ME for milk production) for the average food are used. The approach of energy evaluation that considers all steps of transformation for each food (NE) is more precise; however, to establish a system of NE requires much more knowledge and experimental data. At present, only energy evaluation systems of DE and ME have been used in dogs and cats.

ENERGY EVALUATION

Methods of Estimating Energy in Food

Determination of Energy Content

Digestible energy or ME can be determined only by animal experiments. To determine DE, it is sufficient to collect feces; for ME, in theory, calorimetric methods are required. However, in dogs and cats, fermentation losses by gases can be neglected (Kleiber, 1961; Zentek, 1993), therefore the collection of feces and urine gives results that come very close to ME. A short-cut that combines animal experiments with predictive equations is the correction of experimentally

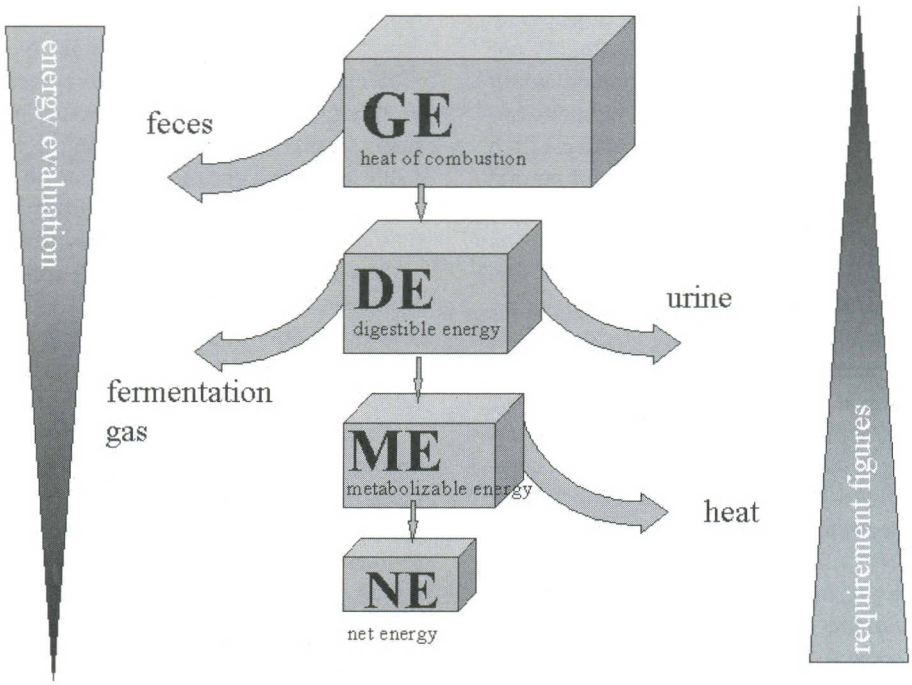

FIGURE 3-1 Principles of bioavailability of energy in animals.

determined DE by predicted energy losses in urine, to estimate ME.

Urine energy losses are predicted by the content of digestible protein. A subtraction is made of 1.25 kcal·g^{-1} digestible crude protein for dogs and 0.9 kcal·g^{-1} digestible crude protein for cats. The factor for cats of 0.9 kcal·g^{-1} digestible crude protein expresses the energy lost by the renal excretion of urea when digested protein is metabolized completely. This factor has been verified experimentally to some extent for cats (National Research Council, 1986); however, Hashimoto et al. (1995) determined an even lower factor for protein correction of DE in cats. For dogs, the correction factor of 1.25 kcal·g^{-1} digestible crude protein has a long tradition tracing back to historic research on energy evaluation by Rubner (1901) and Atwater (1902). Ohshima et al. (1993) investigated the urinary energy losses, but their results were not unequivocal. At present, it is not justified to change the protein correction factors. From a quantitative point of view, the protein correction factor does not matter very much; however, there may be scientific interest to investigate whether a true species difference exists between dogs and cats.

Prediction of Energy Content

Data from Tables

For diets that consist of usual ingredients, data on digestibility of nutrients or ME from tabular values may be used (see Meyer and Zentek, 2001). Either the energy content of digestible nutrients (i.e., heat of combustion of nutrient × digestibility) is summed with the aforementioned subtraction for digestible protein, or ME is taken directly from the table for each ingredient and summed. Data from dogs are often used for cats, which may lead to a slight overestimate of energy digestibility (Kendall et al., 1982a; Figge, 1989. While this approach does not take into account interactions among nutrients and effects of processing, it has been used successfully for homemade and semi-purified experimental diets (Kienzle, 1995). The method cannot be recommended for prepared petfoods for several reasons: for example, the formulation is known only to the manufacturer and the effects of processing on digestibility cannot be taken into account.

Predictive Equations

Factors for nutrients in predictive equations for ME usually reflect the heat of combustion, the digestibility, and a correction for predicted energy losses for protein in urine. Such an equation can predict ME with reasonable precision only if the digestibility of the diets to which it is applied is close to the digestibility of the diets that were used to obtain the equations. The first predictive equation was obtained by Rubner in 1901 for dogs using meat and offal as a food. The factors were later modified by Atwater (1902). The resulting Atwater factors of 4 for protein, 9 for fat, and 4 kcal·g^{-1} for carbohydrate (nitrogen-free extract; NFE) still work amaz-

ingly well for ingredients in homemade diets for dogs: meat, offal (except bones and bone meal), poultry, fish, highly purified starch products, milk products, and even chocolate. In these foods, NFE consists mostly of sugar or starch. Atwater factors are also useful for products that must have a high digestibility, such as milk substitutes and liquids for enteral nutrition.

Given the GE values of 4.1 kcal·g^{-1} carbohydrate, 9.4 kcal·g^{-1} fat, and 5.7 kcal·g^{-1} protein and renal energy losses of 1.25 kcal·g^{-1} digestible protein, Atwater factors include a digestibility of 98 percent for carbohydrate, 96 percent for fat, and 90 percent for protein. Consequently, discrepancies occur when the equation is applied to foods with a higher NSP content such as legumes, salad, fruit, or high-fiber cereal products. For dogs, Atwater factors are still recommended for use for table food if no other data are available, as well as for milk substitutes and liquids for enteral nutrition (Table 3-1). Atwater factors do not work as well for cats because the digestibility of fat is usually somewhat lower in cats than in dogs (Kendall et al., 1982a; Figge, 1989). Provided starchy food is cooked, the factors for carbohydrate (4 kcal·g^{-1}) and protein (4 kcal·g^{-1}) are appropriate for the cat, whereas 8.5 kcal·g^{-1} is recommended to estimate ME for fats in table food (Table 3-2).

When Atwater factors were applied to processed standard diets for dogs, they overestimated the ME content (Kendall et al., 1982b). Therefore, these factors were modified according to the digestibilities of the diets to which they were applied. The modified Atwater factors[1] for dogs and cats (3.5 kcal·g^{-1} protein, 8.5 kcal·g^{-1} fat, 3.5 kcal·g^{-1} carbohydrate) were mostly derived from standard petfoods typically on the market in the 1970s and early 1980s, but they may under- or overestimate the energy content of many products on the market today (Laflamme, 2001; Figure 3-2). The same is true for the equations suggested in 1985 for dry and semimoist food (Laflamme, 2001).

At present, the enormous variability of prepared petfoods on the market with digestibilities of energy ranging from less than 70 percent to more than 90 percent does not allow the use of just one equation with factors for the macronutrients. The variability of digestibilities is not less within product types (dry, moist, semimoist); therefore, the use of different equations for each product type does not solve the problem. Equations have been derived that use the content of either GE or fiber (crude fiber, total dietary fiber, or total fiber) to predict the digestibility of energy (Kendall et al., 1985; Kuhlman et al., 1993; Kienzle et al., 1998a; Schoenmeier, 2003). The use of crude fiber content in equations for prediction of energy digestibility (Tables 3-1 and 3-2) covers a wide range of prepared dog and cat foods (Figure 3-3). However, dog foods with a crude fiber content above 8 percent dry matter and with a high percentage of fermentable NSPs in their crude fiber fraction are systematically underestimated.

Fermentable NSPs will partly or completely disappear during passage through the gastrointestinal tract. Even though they are not digestible by enzymes of the animal, their apparent digestibility will be comparatively high. Consequently, use of the equation to predict energy digestibility, which is based on crude fiber with rather small percentages of fermentable NSPs, will lead to an underestimation of the energy digestibility of high-fiber products with a large percentage of fermentable NSPs in the crude fiber fraction. Fermentable fiber is more likely to be found in the soluble fiber fraction of total dietary fiber and less likely to occur in the insoluble fraction or to be analyzed as crude fiber or acid detergent fiber (see Chapter 4). However, this rule has many exceptions. At present, it is not possible to predict fermentability of fiber by chemical fiber analysis. However, in vitro fermentation may be helpful.

Another simpler explanation for a high apparent digestibility of crude fiber may be that certain proteins from connective tissue may appear analytically as crude fiber. In general, these proteins have a higher apparent digestibility than other compounds determined as crude fiber. In addition, they are not likely to affect the digestibility of other nutrients to the same extent as non-starch polysaccharides or lignin. Whether or not protein appears as crude fiber can be verified by analyzing the residue for nitrogen after boiling in acid and lye. Both the potential use and the adaptation of in vitro digestion and fermentation methods, as well as the potential role of proteins appearing as fiber, need to be investigated further to increase the accuracy of prediction of ME by fiber. However, these points are relevant only for diets with more than 8 percent crude fiber in dry matter; thus, special analyses or in vitro testing can be limited to a few rather special types of diets. For all other diets, the prediction of ME based on fiber produces few outliers. At present, some remaining sources of error such as the above-mentioned differences in apparent fiber digestibility or large differences in food processing are unlikely to be eliminated completely by any equation based on chemical analysis.

In cat food, the variation of fiber content is smaller and the fermentation of fiber also has a smaller role in nutrition of the cat than of the dog. In addition the percentage of the above-mentioned proteins that may be analyzed as fiber

[1]Under model regulations of the Association of American Feed Control Officials, metabolizable energy content statements may be made voluntarily on any commercial dog or cat food label, they are mandatory if the label also bears a calorie-related claim such as "lite" or "less calories" (AAFCO, 2003). The predictive equation for energy content relies on the "modified Atwater" values of 3.5, 8.5, and 3.5 kcal ME·g^{-1} for protein, fat, and NFE, respectively. The same formula is used for both dog and cat foods, irrespective of relative fiber content or presumed digestibility. Hence, it may tend to underestimate energy content of highly digestible foods and overestimate those of less digestibility. Depending on the intended use of the product and the manufacturer's marketing strategy, the predictive equation may not be suitably accurate in its determination of ME content. Thus, manufacturers are also given the option of determining energy content on the basis of results of a feeding trial (see Chapter 2).

BIBLIOTECA DE CIENCIAS
BIOLOGICAS Y AGROPECUARIAS

TABLE 3-1 Predictive Equations for Metabolizable Energy in Dog Food

Application	Equation
Unprocessed food or human food such as meat, offal, milk products, cooked starch sources; highly digestible special products such as milk substitutes or diets for enteral nutrition[a]	ME (kcal) = (4 × g protein) + (9 × g fat) + (4 × g NFE)
Prepared dog foods[b]	*Step 1:* Determine GE by bomb calorimetry or calculate GE by the following equation: GE (kcal) = (5.7 × g protein) + (9.4 × g fat) + [4.1 × (g NFE + g fiber)] *Step 2[c]:* Percentage energy digestibility = 91.2 – (1.43 × percentage crude fiber in dry matter) *Step 3:* DE (kcal) = (GE × percentage energy digestibility/100) *Step 4:* ME (kcal) = DE – (1.04 × g protein) *Example:* Food composition: 80% moisture, 7% protein, 4% fat, 3% ash, 1% crude fiber, 5% NFE *Step 1:* GE (kcal·g^{-1}) = 5.7 × 0.07 + 9.4 × 0.04 + 4.1 × (0.01+ 0.05) = 1.02 *Step 2:* Percentage energy digestibility = 91.2 – (1.43 × 1/20 × 100) = 84.05% *Step 3:* DE (kcal·g^{-1}) = 1.02 × 84.05/100 = 0.86 *Step 4:* ME (kcal·g^{-1}) = 0.86 – 0.07 × 1.04 = 0.79

[a]This equation is valid only for food with a digestibility of energy >90%. It must be applied only to prepared dog foods with an exceptionally high digestibility such as milk substitutes or liquid preparations for enteral nutrition, which must be highly digestible to fulfill their function.
[b]Not including milk substitutes and liquid preparations for enteral nutrition. May be inaccurate if crude fiber is >8% dry matter.
[c]Alternative equation using total dietary fiber (American Organization of Analytical Chemists): percentage energy digestibility = 96.6 – (0.95 × percentage total dietary fiber in dry matter).

TABLE 3-2 Predictive Equations for Metabolizable Energy in Cat Food

Application	Equation
Unprocessed food or human food such as meat, offal, milk products, cooked starch sources; highly digestible special products such as milk substitutes or diets for enteral nutrition[a]	ME (kcal) = (4 × g protein) + (8.5 × g fat) + (4 × g NFE)
Prepared cat foods[b]	*Step 1:* Determine GE by bomb calorimetry or calculate GE by the following equation: GE (kcal) = (5.7 × g protein) + (9.4 × g fat) + 4.1 × (g NFE + g fiber) *Step 2[c]:* Percentage energy digestibility = 87.9 – (0.88 × percentage crude fiber in dry matter) *Step 3:* DE (kcal) = (GE × percentage energy digestibility/100) *Step 4:* ME (kcal) = DE – (0.77 × g protein) *Example:* Food composition: 80% moisture, 7% protein, 4% fat, 3% ash, 1% crude fiber, 5% NFE Step 1: GE (kcal·g^{-1}) = 5.7 × 0.07 + 9.4 × 0.04 + 4.1 × (0.01 + 0.05) = 1.02 Step 2: Percentage energy digestibility = 87.9 – (0.88 × 1/20 × 100) = 83.5% Step 3: DE (kcal·g^{-1}) = 1.02 × 83.5/100 = 0.85 Step 4: ME (kcal·g^{-1}) = 0.85 – 0.07 × 0.77 = 0.80

[a]This equation is valid only for food with a digestibility of energy >90%. It must be applied only to prepared cat foods with an exceptionally high digestibility such as milk substitutes or liquid preparations for enteral nutrition, which must be highly digestible to fulfill their function.
[b]Not including milk substitutes and liquid preparations for enteral nutrition.
[c]Alternative equation using total dietary fiber (American Organization of Analytical Chemists: Percentage energy digestibility = 95.6 – (0.89 × percentage total dietary fiber in dry matter)).

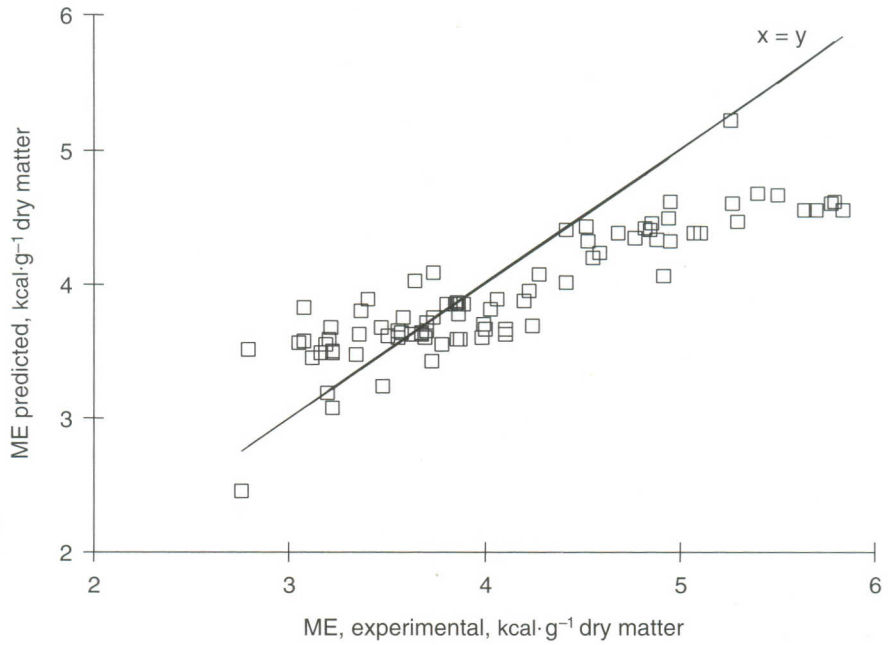

FIGURE 3-2 Comparison of experimentally determined and predicted ME values in prepared cat food. *y* axis = ME predicted by modified Atwater factors: 3.5 kcal·g^{-1} for protein and carbohydrate, 8.5 kcal·g^{-1} for fat; *x* axis = ME determined by digestion trials, with ME = DE – 0.9 kcal·g^{-1} digestible protein (data from Kienzle, 2002). Ideally, all points should be on the line $x = y$.

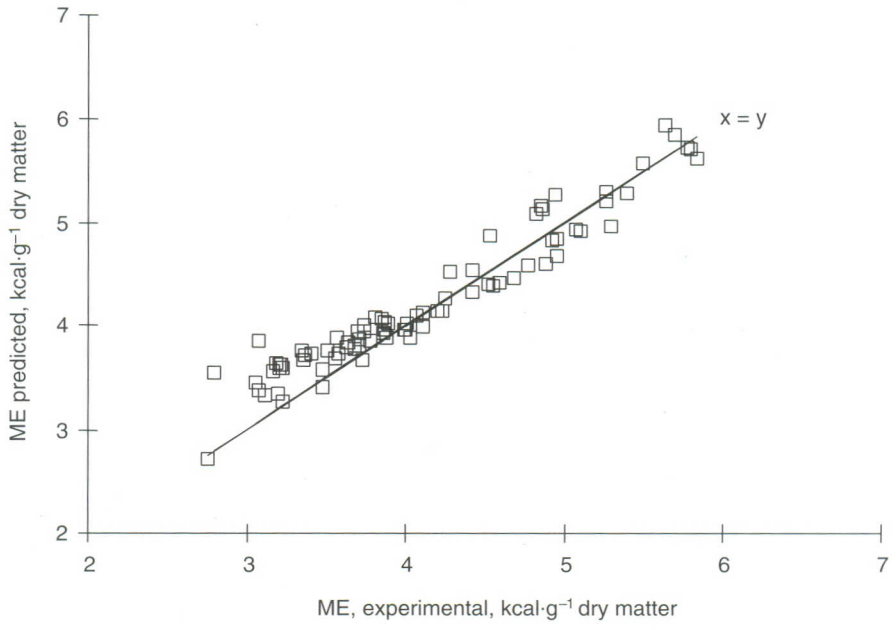

FIGURE 3-3 Comparison of experimentally determined and predicted ME values in prepared cat food. *y* axis = ME predicted by equations based on GE and crude fiber: GE by bomb calorimetry; percentage energy digestibility = 87.9 – (0.88 × percentage crude fiber in dry matter); ME (kcal) = (GE × percentage energy digestibility/100) – (0.77 × g protein). *x* axis = ME determined by digestion trials, with ME = DE – 0.9 kcal·g^{-1} digestible protein (data from Kienzle, 2002). Ideally, all points should be on the line $x = y$.

may be smaller in cat foods explaining why the accuracy of prediction of ME based on crude fiber content is higher for cat foods than for dog foods, even though the equation is based on fewer observations. Another point is that fiber has a lower impact on fat digestibility than on NFE digestibility. Kienzle et al. (2001) suggested different equations for the estimation of energy digestibility as a function of fiber for high- and low-NFE diets for dogs. The smaller decrease of digestibility per percentage of fiber in dry matter in the equation for cat food than in the equation for dog food is unlikely to be a species difference. It probably reflects a smaller range of NFE content in cat food than in dog food.

Thus far, equations to estimate energy digestibility as a function of fiber have been based mainly on crude fiber analysis for practical reasons. Crude fiber is most often used for labeling petfoods; consequently, there are much more data on crude fiber and energy digestibility than on any other fiber analysis. Kienzle et al. (1998b) demonstrated that it is possible to predict energy digestibility as a function of fiber with other methods of fiber analysis as long as the major percentage of cellulose is determined. Recently, Schoenmeier (2003) developed a prediction equation for energy digestibility as a function of total dietary fiber (American Organization of Analytical Chemists [AOAC] method). To predict ME with either of these regression equations, GE (determined or calculated) is multiplied by the digestion coefficient to calculate DE. A subtraction is made from DE for urinary energy losses using a mean digestibility of protein of 83.5 percent in dogs and 86 percent in cats and a mean loss of energy in urine per gram of digestible crude protein of 1.25 kcal for dog foods and 0.9 kcal for cat foods.

There is no universal predictive equation that fits any food a dog or cat may eat; therefore, an important consideration before using any equation is its validity for the food in question. In general, the use of unmodified Atwater factors for commercial products will overestimate ME. However, for casein-based milk substitutes with an appropriate digestibility, unmodified Atwater factors may be the predictive equation of choice, whereas modified Atwater factors will grossly underestimate energy and prediction of energy digestibility by fiber content will also lead to errors.

ENERGY REQUIREMENTS OF DOGS

Definitions

A minimal amount of energy—the basal metabolic rate—is required each day to maintain body weight even in the absence of factors that increase energy consumption such as physical activity, food consumption, or a low environmental temperature.

Basal metabolic rate (BMR) is defined as the energy required to maintain homeostasis in an animal in a post-absorptive state (ideally after an overnight fast) that is lying down but awake in a thermoneutral environment to which it has been acclimatized (Blaxter, 1989). As an alternative, the *resting fed metabolic rate (RFMR)*, is measured in animals that are not in a post-absorptive state, but otherwise meet the criteria for basal metabolism. Heat production increases when food is consumed. This dietary thermogenesis or thermic effect of food represents the difference between RFMR and BMR. Dietary thermogenesis has two components: an obligatory component associated with the ingestion, digestion, absorption, and assimilation of food (the heat increment or specific dynamic effect of food); and a facultative component associated with activation of the autonomic nervous system.

The *maintenance energy requirement (MER)* is the energy required to support energy equilibrium, (where ME intake equals heat production), over a long period of time (Blaxter, 1989). Thus, MER may vary with any factor that affects heat production. It includes energy required for thermoregulation, spontaneous activity, and moderate exercise. The term MER is, therefore, qualified in the following discussion by the conditions to which it refers. Effects of environmental temperature and strenuous exercise on energy requirements are described in detail in Chapter 11.

Basis for Establishing Energy Requirements

Allometric considerations of metabolic body weight are of paramount importance in dogs, a species in which mature body weights may range from 1 to 90 kg or more. From a physiological viewpoint, energy requirements of animals with widely differing weights are not related directly to body weight but are more closely related to body weight raised to some power, W^b, where W equals weight in kilograms and b is an exponent calculated from experimental data. Brody et al. (1934) found that the basal heat production for mature, warm-blooded animals, ranging in size from mice to elephants, could be described by the expression $Y = 70.5 \times W^{0.73}$, where Y equals kilocalories per 24 hours and W equals body weight in kilograms. Before calculators and computers were readily available, Kleiber (1961) argued that over such a range in body size, results using the expression $Y = 70 \times W^{0.75}$ would not differ significantly from those of Brody, and would be simpler to use.

Heusner (1982) argued that the interspecific mass exponent in Kleiber's equation is a statistical artifact. He suggested that the theoretical exponent should be 0.67 to predict the intraspecies relationship of energy to mass. This theoretical exponent describes the relationship between mass and body surface in bodies that are geometrically similar. However, dogs of varying breeds and body sizes are not geometrically similar (Kirkwood, 1985). For instance, with increasing size, dogs become relatively taller at the shoulder and relatively narrower at the hip. Brain and several visceral organs including liver and gastrointestinal tract become relatively smaller with increasing mature weight (Meyer et al.,

1993), a trend that also occurs among species even if not at the same rates (Kirkwood, 1985). Blood volume and heart mass, even heart rate, change with size among dogs at rates similar to those seen in a variety of species (Kirkwood, 1985). All these findings suggest that the interspecies mass exponent from Kleiber's equation (0.75) may be more suitable to describe the relation between mass and energy in dogs than the intraspecies mass exponent suggested by Heusner (1982).

Variation of the energy requirements of breeds may be superimposed on the relationship between body mass and energy. Breeds of similar size and weight can differ greatly in energy requirements. Blaza (1981) reported that the energy requirements of Great Danes expressed on a metabolic body weight basis (mass exponent 0.75) are higher than those of other dogs. She also postulated higher requirements for Newfoundlands. However, later work of Kienzle and Rainbird (1991) demonstrated in a larger group of dogs that the energy requirements of Newfoundlands are 20 percent below average but confirmed that Great Danes are up to 60 percent above average.

Other factors that influence energy requirements, such as age, may not be equally distributed among weight groups and thus can create statistical artifacts for the optimal mass exponent. Rainbird and Kienzle (1990) considered only middle-aged dogs of breeds without known peculiarities in energy requirements under similar housing conditions to calculate the mass exponent and came up with a value that was very close to the interspecies exponent of Brody's equation. Therefore, varying the mass exponent does not increase the accuracy of prediction of energy requirements of dogs. The goal must be to identify or more clearly describe factors affecting individual energy requirements such as breed, age, housing, and their interactions.

A very important point that cannot be addressed by body weight, but is, however, affected by feeding, breed, age, and activity, is the percentage of lean body mass. Adipose tissue is metabolically less active than lean body mass. Therefore, dogs with a smaller percentage of lean body mass (e.g., overweight dogs) have below-average energy requirements for their body weight (BW). Beagles with normal weight (25 percent fat in total body) had an energy expenditure measured by the doubly labeled water method of 130 ± 6 kcal·kg $BW^{-0.75}$. The same dogs were overfed for a period of time until their body fat content was 38 percent, decreasing their energy expenditure to 107 ± 7 kcal·kg $BW^{-0.75}$. The energy requirement per unit of lean body weight (157 kcal·kg $BW^{-0.75}$) did not differ significantly according to body condition (Pouteau et al., 2000). It is likely that these findings also apply to other reasons for decreases in lean body mass, such as lack of exercise for a prolonged period or old age. At present, the energy requirements of an individual dog cannot be more than an educated guess and can easily miss the true requirements by 50 percent.

Basal Metabolic Rate

Many authors have attempted to measure BMR in dogs using indirect calorimetry in conscious and anesthetized dogs (see Table 3-3). Kunde and Steinhaus (1926) suggested that higher values for BMR obtained by Rubner and Boothby and Sandiford were not necessarily basal, but others (Kitchen, 1924; DeBeer and Hjoort, 1938) have also reported high values for BMR. The parabolic relationship between body weight and BMR in anesthetized dogs reported by Udall et al. (1953), when converted to an exponential relationship, also suggested a higher value for BMR (91 kcal·kg $BW^{-0.75}$) in dogs. These authors did not report individual data. Data from individual dogs (Table 3-3) provided by several authors give a BMR of 76 ± 23 kcal·kg $BW^{-0.75}$. This approximates Kleiber's interspecies estimate of 70 kcal·kg $BW^{-0.75}$ for minimal metabolism, but individual values vary widely from 48 to 114 kcal·kg $BW^{-0.75}$. Okarma and Koteja (1987) reported the mean BMR of gray wolves

TABLE 3-3 Basal Metabolic Rate in Dogs

				Daily BMR (kcal ME·kg $BW^{-0.75}$)		
Animals	Gender[a]	BW (kg)	*n*	Mean ± 2 SD	Range	Source
Dogs	M	5-26	8	89 ± 24	78-114	Rubner[b]
Dogs	MF	10-15	7	71 ± 9	63-78	Kunde[b]
Dogs	MF	12-17	4	85 ± 27	76-105	Boothby and Sandiford[b]
Dogs	F	9-16	11	71 ± 12	60-82	Lusk and Dubois[b]
Dogs	M	9-27	6	67 ± 14	59-77	Steinhaus[b]
Dogs	MF	10-18	13	85 ± 22	72-106	Kitchen, 1924
Bull terriers	MF	20-27	11	81 ± 4	78-83	DeBeer and Hjoort, 1938
Dogs	M	3-28	31	70 ± 22	48-88	Galvao, 1947
Dogs	F	8-10	3	70 ± 20	58-77	Hammel et al.,1958
Mongrels	NA	18 ± 3	5	54 ± 9		Leblanc and Diamond, 1986

NOTE: SD = standard deviation.

[a]M = male, F = female, NA = not available.

[b]Cited in Kunde and Steinhaus (1926).

(purportedly the ancestor of the domestic dog) was similar (68 kcal·kg $BW^{-0.75}$).

Diet-Induced Thermogenesis and Resting Fed Metabolic Rate

The ingestion, digestion, absorption, and assimilation of food requires energy and increases heat production. Thus, RFMR is slightly higher than BMR, and this difference is termed dietary thermogenesis, the specific dynamic effect of food, or diet-induced thermogenesis. Dietary thermogenesis is not considered useful to the animal except at low ambient temperatures where it may contribute to maintenance of body temperature. Thus, the proportion of ME retained by the animal represents the efficiency of utilization of ME (Blaxter, 1989).

The heat increment is measured by dividing the change in heat produced by the change in ME intake when animals are fed two different amounts of ME (Blaxter, 1989). This heat increment is usually expressed as a percentage of ME and varies with the amount and composition of food consumed. For example, the thermic effect of glucose is less if glucose is used immediately after ingestion, but efficiency is lower if glucose is first stored as glycogen or fat. In simple-stomached animals, Blaxter (1989) estimated that the heat increment for protein, fat, and carbohydrate was 23, 2, and 6 percent, respectively, below maintenance, and 36, 15, and 22 percent, respectively, above maintenance. In dogs consuming an average diet, Blaxter (1989) estimated the heat increment to be 15 percent below maintenance and 30 percent above maintenance. This would suggest that RFMR is 15 percent above BMR in normal adults and that the difference would be greater in growing, pregnant, and lactating animals. Nevertheless, measurements of heat increment tend to give high estimates of the thermic effect of food because voluntary activity increases with the amount of food that animals are fed and it is impossible to limit activity during the long periods required for measurements to be made (Blaxter, 1989).

In humans, the specific dynamic effect of food is commonly measured as the total increase in heat production over time after a single meal (Blaxter, 1989). A similar methodology has also been used to measure dietary thermogenesis in other simple stomached species. In gray wolves, for example, Okarma and Koteja (1987) reported that metabolic rate increased by 47 percent after a high protein meal but did not report the duration of this effect. In mongrel dogs, Diamond et al. (1985) reported that dietary thermogenesis after a meal had two phases. There was an immediate cephalic phase when catecholamines were released into the circulation and when metabolic rate increased in response to the taste and smell of food (Diamond and Leblanc, 1987). This phase lasted 40-50 minutes and was present even in sham fed animals (Diamond et al., 1985; Leblanc and Diamond, 1986). After the cephalic phase, there was a post-absorptive phase that lasted up to 6 hours after a meal and was not associated with an increase in circulating catecholamines (Diamond et al., 1985; Leblanc and Diamond, 1986).

After a mixed meal of unstated composition, the metabolic rate increased during the 50 minutes of the cephalic phase to a peak that was 75 percent above the fasting rate irrespective of the size of the meal (Leblanc and Diamond, 1986). This cephalic phase occurred four times in dogs fed four meals daily but only once in dogs fed the same amount of food daily. Dietary thermogenesis was greater in dogs fed four meals daily than in dogs fed once daily (Leblanc and Diamond, 1986). The postprandial phase was of smaller amplitude but of longer duration and varied in size in proportion to the size of each meal. Over 11 hours, taking both phases into account, the metabolic rate increased by an average of 13 percent in dogs fed a single 85 kcal·kg $BW^{-0.75}$ meal but increased an average of 25 percent in dogs given the same amount of food as four smaller meals (Leblanc and Diamond, 1986). Over the whole day, this would represent an increase of 6 percent and 11 percent, respectively, when dogs were daily consuming slightly more food than was sufficient to maintain body weight. Nevertheless, dietary thermogenesis measured in this way may give low estimates of the thermic effect of food because it may not take account of the cost of maintaining the metabolic machinery needed at any given level of intake. In dogs, therefore, this suggests that dietary thermogenesis represents approximately 10 percent of daily energy expenditure and RFMR is probably 10 percent higher than BMR. This difference will be slightly less in dogs fed once daily and slightly more in dogs fed several times daily.

Dietary thermogenesis could be greater if the diet is high in protein, but the effect is likely to be very small. Protein would only affect the obligatory component and would be less likely to affect the increment caused by anticipation of a meal. Anxiety, exercise, and cold-induced thermogenesis all have a much larger effect on heat production. Overconsumption of food in rats may cause catecholamines to be released into the circulation, causing an additional increase in heat production above the obligatory heat increment. This diet-induced thermogenesis has a regulatory effect on body weight because it minimizes the increase in body weight associated with overeating. There appears to be no similar diet-induced thermogenic response to overeating in dogs, however (Crist and Romsos, 1987).

Adult Maintenance

From a relatively small number of observations (Cowgill, 1928; Abrams, 1962) based partly on calculations of Arnold and Elvehjem (1939) from the prediction equation of Brody et al. (1934), the National Research Council (1974) suggested calculating the maintenance energy requirements of dogs by the equation 132 kcal $\times$ $BW^{0.75}$. This has been questioned after the above-mentioned observations on Great

Danes by Blaza (1981) and because of lower values for energy requirements reported in direct or indirect calorimetric studies (Burger and Johnson, 1991; Maenner, 1991; Walters et al., 1993). However, a large number of relatively new data (Rainbird and Kienzle, 1990; Kienzle and Rainbird, 1991; Finke, 1991, 1994; Ballevre et al., 1994; Table 3-4) demonstrate that the equation 132 kcal $\times$ $BW^{0.75}$ is valid for lively younger experimental dogs kept in kennels.[2] The point, however, should be stressed that there is considerable individual variation, even between dogs kept under the same conditions. Ninety-five percent of the individuals within the population are within the range of the mean plus or minus the double standard deviation. The recommendations in Table 15-4 (Chapter 15 *Nutrient Requirement Tables*) should be considered as the place to start.

Newfoundlands, Great Danes, and terriers living in kennels have been identified as breeds with energy requirements outlying the predictive range (Table 3-4). Young adult dogs have above-average energy requirements and old dogs have decreased energy requirements. The time of the respective changes in energy requirements appears to be dependent somewhat on breed (Kienzle and Rainbird, 1991; Finke, 1994). It is probable that larger breeds that age early will also show a decrease in energy requirements at a comparatively earlier age. Age effects are thought to be due partly to differences in activity and their consequences (Donoghue et al., 1991). This is in good agreement with reports on the energy requirements of pet dogs (Burger, 1994; Wichert et al., 1999; Connor et al., 2000; Patil and Bisby, 2001). Pet dogs without opportunity and stimulus to exercise need between 10 and 20 percent less energy than experimental dogs; Patil and Bisby (2001) strongly suggested a link to activity in pet dogs. The lowest maintenance energy requirements described for pet dogs come rather close to the RFMR of about 90 kcal·kg $BW^{-0.75}$ measured by Walters et al. (1993) in client-owned dogs after adaptation to indirect calorimetry.

The effects of breed, age, and environment on energy requirements are likely not entirely additive. A large part of these effects is the result of differences in activity level as well as differences in lean body mass. Consequently, the energy requirements of an inactive kennel dog are not much different from those of an inactive in-home pet if similar environmental temperature, stress level, and lean body mass are assumed. The latter may differ, however, between a pet dog that has been inactive for a considerable period of time and a kennel dog that is only temporarily restricted in physical activity. Other effects on energy requirements, such as differences in digestive capacity among breeds (Zentek and Meyer, 1993), appear to be additive. For "bedside calculations" of energy requirements in clinical practice, linear equations may be useful. From the data mentioned above the equation for energy requirements in kilocalories = 358 + 39 $\times$ BW was derived giving similar results to the powered equation for dogs between 8 and 20 kg BW. Age, breed, and other factors affecting energy requirements can be considered by reducing or increasing the calculated value by the appropriate percentages, for example by decreasing the result by 20 percent for an old dog. There are no unequivocal effects of gender on energy requirements of dogs. The effect of neutering is probably an indirect one since neutering often leads to a relative decrease of lean body mass. Illness and trauma can affect energy requirements dramatically. Severe illness or trauma may even double the energy requirements (Donoghue, 1991). However, most quantitative data are transferred from human patients. There may be species differences. A recent study that found higher content of body fat in female dogs with mammary tumors compared to controls (Lawler and Ballam, 2001) invites some speculation.

[2]Stress level, activity, and energy requirements of dogs in kennels might also differ in relation to the type of kennel in which the dogs are housed.

Gestation

Weight increase in bitches during pregnancy of 20 to 25 percent occurs mainly after the 28th day of gestation (Siedler and Schweigert, 1954; Romsos et al., 1981). The total weight of the litter averages about 13.5 percent of the bitch weight after parturition (Meyer et al., 1985a). Smaller breeds in general have smaller litters; however, the relative birth weight of puppies is higher; therefore, differences in litter weight related to body size are small. In total, about two-thirds of the weight gain of the bitch is accounted for by the weight of the puppies, placentas (about 22 percent of puppy weight), and intraplacental fluid. The rest is water and extrauterine increase of body mass. It is a notable allometric feature that total litter mass as well as increase of body weight during pregnancy are directly related to body weight. The intrauterine growth of puppies is not a linear function of time (Evans, 1974).

Considerable weight gain of fetuses occurs only after the 40th day of pregnancy. Additional energy for building fetal tissue is assumed to be required mainly during this period. However, bitches often tend to eat less during the last days of pregnancy. In addition, extrauterine tissue of the bitch may start increasing before the 40th day of pregnancy. Therefore, it is recommended that feeding extra energy for pregnancy start 4 weeks after mating. Meyer et al. (1985a) estimated—factorial calculations from litter weight and puppy body composition; placental weight and composition; and by estimation for extrauterine tissue of the bitch—that the requirements for later gestation (4 weeks after mating until parturition) would be 26 kcal·kg $BW^{-1}\cdot d^{-1}$. Using the mean energy requirements of a kennel dog (130 kcal·kg $BW^{-0.75}$) as a starting point, the energy requirements of a pregnant bitch amount to 130 percent of maintenance in a 5-kg bitch and 160 percent of maintenance in a 60-kg bitch (Table 15-6). The factors affecting fluctuation in maintenance energy requirements appear to continue during preg-

TABLE 3-4 Reported Maintenance Energy Requirements of Dogs in Relation to Breed, Age, Housing, and Activity

Breed, Age (years), Housing, Activity	ME (kcal ME·kg $BW^{-0.75}$) Mean ± 2SD[a]	*n*	Reference
Large-sized pet dogs	94 ± 50		Patil and Bisby, 2001
Pet dogs	95 ± 40	28	Wichert et al., 1999
Inactive pet Border collies	97 ± 82	9	Burger, 1994
Old laboratory Labradors (9)	103 ± 22	6	Finke, 1991
Old laboratory Labradors (>7)	104 ± 32	14	Rainbird and Kienzle, 1990
Pet dogs	105 (range 60-200)	48	Connor et al., 2000
Middle-aged laboratory Newfoundlands (3-7)	106 ± 26	26	Rainbird and Kienzle, 1990
Old laboratory dogs of various breeds (>8)	107 ± 14	11	Taylor et al., 1995
Old laboratory beagles (>10)	110 ± 26	5	Finke, 1994
Middle-aged laboratory beagles (3-10)	114 ± 16	8	Finke, 1994
Middle-aged laboratory beagles (4)	117 ± 18	6	Finke, 1991
Middle-aged laboratory dogs (3-7)	124 ± 42	86	Rainbird and Kienzle, 1990
Moderately active pet Border collies	124 ± 88	28	Burger, 1994
Young laboratory dogs of various breeds (<6)	129 ± 10	12	Taylor et al., 1995
Young to middle-aged laboratory huskies (1-7)	132 ± 20	5	Finke, 1991
Laboratory beagles	132 ± 40		Patil and Bisby, 2001
Medium-sized pet dogs living in multiple dog households	133 ± 52		Patil and Bisby, 2001
Laboratory Labradors	138 ± 32		Patil and Bisby, 2001
Young laboratory dogs (1-2)	139 ± 42	69	Rainbird and Kienzle, 1990
Young laboratory beagles (1-2)	144 ± 28	6	Finke, 1994
Highly active pet Border collies	175 ± 170	10	Burger, 1994
Laboratory terriers	183 ± 48		Patil and Bisby, 2001
Great Danes, outdoor kennels, summer	Around 200	7	Zentek and Meyer, 1992
Great Danes, outdoor kennels, winter	Around 250	7	Zentek and Meyer, 1992

[a]95 percent of the population are within this range.

nancy. Zentek and Meyer (1992) reported that Great Danes consumed somewhat less energy during the second half of pregnancy, when they were housed indoors and were less active, than during the first half, when they were outdoors and more active. These factors are, however, unlikely to affect the requirements for building fetal and extrauterine tissue during pregnancy. Therefore, it is recommended that the energy requirements of individual pregnant bitches be calculated starting from their individual maintenance requirements per kilogram of $BW^{0.75}$ and adding 26 kcal·kg BW^{-1} rather than calculating as percentages of maintenance.

Lactation

Bitches suckle their puppies in general for at least 6 weeks. Offering food to puppies may be started at 2½ weeks of age at the earliest but should begin by week 4 of lactation at the latest. At that age, the quantity and nutrient content of the milk are no longer appropriate. It is possible to wean puppies at that stage of lactation; however, this is not recommended because it may have undesirable effects on imprinting of puppies, which could induce behavior problems later on (Feddersen-Petersen and Ohl, 1995).

Milk yield and energy content in milk are important factors in estimating the energy requirements for milk production. Ruesse (1961) investigated these variables in several bitches from various breeds for a few days and in one German Shepherd bitch during the length of lactation. Oftedal (1984) determined milk yield and milk composition of beagles. Meyer et al. (1985b) investigated these variables as well as food intake and weight changes in several breeds ranging in size from 4 to 24 kg. Zentek and Meyer (1992) described the food intake and weight changes of Great Danes during lactation. Scantlebury et al. (2000) investigated the energetics of lactation in Labrador retrievers and miniature schnauzers.

From the nutrient content of bitch milk, the gross energy content is estimated to amount to about 1.45 kcal·g^{-1} wet weight. The energy content of canine milk shows little variation except for the colostral period (Meyer et al., 1985b). Milk yield has been estimated to amount up to 8 percent of body weight (Ruesse, 1961; Oftedal, 1984; Meyer et al., 1985b; Scantlebury et al., 2000). These studies agree that peak lactation in the bitch occurs in the 4th week. The lactation curve during the first 4 weeks is based on a considerable amount of data (Meyer et al., 1985b); however, thereafter information is scarce. This results from methodological problems in determining milk yield at that stage, when puppies need to be given additional food. Ruesse (1961) investigated the complete lactation of a German Shepherd bitch. A rather rapid decrease of milk yield after puppies were given additional food was observed. However, after the 4th week of lactation the suckling behavior of bitches may differ considerably, some tolerating sucking by their puppies

for a considerable time, others not. Therefore after 4 weeks of lactation milk yield will show a considerable individual variation. At present, a reasonable estimate is only possible for the first 4 weeks of lactation. Expressed as a percentage of the mean daily milk yield during the first 4 weeks of lactation, milk production is as follows: 75 percent in week 1, 95 percent in week 2, 110 percent in week 3, and 120 percent in week 4.

An important determinant of milk yield appears to be the number of sucking puppies (Meyer et al., 1985b). With one to four puppies in the litter, daily milk yield increases nearly linearly by about 1 percent of bitch body weight per puppy. Thereafter, the increase is no longer linear. With five to eight puppies, the increase in daily milk yield per puppy is about 0.5 percent of bitch body weight. When there are more than eight puppies in the litter, there is no further notable increase of daily milk yield per puppy.

The energy requirements for milk production can be calculated factorially from these figures. As a first step, the milk energy output can be calculated from milk yield and GE in milk as follows: milk yield (g·kg BW^{-1}) × 1.45 kcal. The result would represent net metabolic energy need for milk production. The utilization of ME for milk production is assumed to be 60 percent, an assumption that is based mainly on the work of Scantlebury et al. (2000) and analogous to other species. Therefore, the ME requirement for milk production is calculated as follows: ME = milk yield (g·kg BW^{-1}) × 1.45 kcal/60 × 100 = milk yield (g·kg BW^{-1}) × 2.42 kcal. Daily milk yield can be estimated by the number of puppies per litter. For one to four puppies, it is 1 percent of bitch weight per puppy, (i.e., the ME requirement for milk production per puppy is 10 × 2.42 kcal·kg BW^{-1} of bitch = 24 kcal·kg BW^{-1} of bitch per puppy). With five to eight puppies, daily milk yield is only 0.5 percent of bitch weight. Daily ME requirements for milk production per puppy are therefore 5 × 2.42 kcal·kg BW^{-1} = 12 kcal·kg BW^{-1} of bitch per puppy. To calculate requirements for milk yield, the number of puppies between one and four is multiplied by 24 kcal·kg BW^{-1} of bitch and the number of puppies between five and eight is multiplied by 12 kcal·kg BW^{-1} of bitch and the results summed.

The maintenance requirement must be considered separately. A bitch rearing a litter can be considered to be quite active. Meyer et al. (1985b) calculated a linear regression between the milk yield of bitches as an independent variable and the energy intake (corrected for variations in body weight) as the dependent variable extrapolated for zero milk production. The intercept of the regression equation can be considered to represent maintenance requirements, 145 kcal·kg $BW^{-0.75}$. No studies have investigated whether maintenance energy requirements during lactation differ according to breed, environmental temperature, and other individual or environmental factors. For bitches having large litters, variation of maintenance energy requirements is not likely to be very important because maintenance requirements represent a relatively small percentage of their total energy requirements. In bitches with small litters, individual differences in maintenance energy requirements are more likely to affect total energy requirements during lactation to an extent that is of practical significance. Maintenance energy requirements for lactation of 145 kcal·kg $BW^{-0.75}$ should be considered as an appropriate starting point (the basis for total requirements in Table 15-7). This equation is suitable for computer programs and agrees very well with results from feeding experiments (Meyer et al., 1985b; Scantlebury et al., 2000).

For bitches with large litters the capacity for food intake can limit energy intake. This is especially true in large and giant breeds because the relative size of the gastrointestinal tract decreases with increasing body size. Small- and medium-sized breeds can increase their dry matter intake during lactation to around 4.5 percent of their body weight; some individuals may even reach an intake of up to 9 percent of body weight. Meyer and Zentek (1992) demonstrated that Great Danes do not eat more dry matter than 2.5-3.2 percent of their body weight even if they suckle a large litter. Energy requirement and the capacity for food intake determine the minimal energy density of the food that should be used. In Great Danes—and possibly other giant breeds as well—it may be necessary, even if high-energy diets are fed to the bitch, to give additional food to the puppies at a very early age.

Growth

Newborn puppies need about 25 kcal/100 g BW (Kienzle et al., 1985). Growing puppies require about two times as much energy per unit of body weight as adult dogs of the same breed (Arnold and Elvehjem, 1939). The newly weaned dog can readily adapt to this level of feeding, particularly when the food is offered in multiple, judiciously spaced meals. However, an arbitrary decrease to 1.6 times maintenance is recommended when 50 percent of adult body weight has been reached and 1.2 times maintenance at 80 percent of adult weight. This reduction compensates for the decline in energy required from weaning to adult age. Especially in large and giant breeds, optimal—not maximal—growth is an important factor for proper skeletal development. Hedhammar et al. (1974) were the first to demonstrate that overfeeding can result in growth disorders; however, in that experiment, excess energy and several other nutrients including protein and calcium were fed. Feeding too much energy in combination with a well-balanced intake of all other nutrients will induce growth disorders in predisposed breeds such as Great Danes (Meyer and Zentek, 1992). Recommendations for the weight development of large and giant breeds are given in Table 3-5. The individual large- or giant-breed puppy should be fed to meet these recommendations rather than being fed according to energy requirement figures.

TABLE 3-5 Recommendations for Growth of Large- and Giant-Breed Dogs

Age (months)	Medium Breeds (mature weight 20 kg)		Large Breeds (mature weight 35 kg)		Giant Breeds (mature weight 60 kg)	
	BW (kg)	% mature BW	BW (kg)	% mature BW	BW (kg)	% mature BW
1	1.8	9	2.5	7	3.6	6
2	4.4	22	7.0	20	8.4	14
3	7.4	37	12.3	35	15.6	26
4	10.4	52	16.8	48	22.8	38
6	14.0	70	22.8	65	36.0	60
12	19.0	95	30.8	88	48.0	80

Factorial approaches have been used to calculate energy requirements from data on puppy growth and body composition for different stages of growth and different mature body weights (Society of Nutrition Physiology, 1989). Meyer and Zentek (1992) carried out feeding experiments with Great Danes and arrived at somewhat higher figures for large breeds than the Society of Nutrition Physiology. Meyer and Zentek (1998) published recommendations based on the data of the Society of Nutrition Physiology and their own experiments. Blanchard et al. (1998) proposed an equation to calculate energy requirements for growing puppies after weaning (Table 15-2) that was based mainly on recommendations from the National Research Council (1985). This equation agrees well with those of Meyer and Zentek (1998) provided the puppies grow according to the growth recommendations in Table 3-4. Such an equation (Table 15-2) is well suited for computer programs and also has the advantage of providing requirements for puppies that do not grow according to recommendations, a situation that is encountered in nutrition consultation.

The question arises as to whether breed differences and other factors affecting maintenance energy requirements should be considered during growth. The existing data do not provide a definite answer. However, results are available indicating that the activity level has a similar effect during growth as during maintenance. Rainbird and Kienzle (1990) demonstrated that Great Danes ate more during growth than Newfoundlands. As the Great Danes grew more rapidly than the Newfoundlands, it is difficult to differentiate between effects of activity level (the Newfoundlands were less active) and growth rate. In the last months of the observation period (8th to 12th month of life), the differences in growth rate were considerably smaller, and the differences between energy intake were even larger than during the beginning of the growth period. Wichert et al. (1999) observed lower energy intake in pet puppies (assumed lower activity than kennel puppies) growing according to recommendations. The energy intake was about 10 to 20 percent lower than values calculated by the equation of Blanchard et al. (1998) using a maintenance energy requirement of 132 kcal·kg $BW^{-0.75}$. It appears prudent and justified to consider possible differences in maintenance energy requirements as a result of differences in activity level at least during the second half of the growth period.

Physical Activity

Effects of physical activity on energy requirements are discussed in Chapter 11.

ENERGY REQUIREMENTS OF CATS

Basis for Establishing Energy Requirements

The mature body weight of domestic cats (*Felis catus*) ranges from less than 2 to more than 7 kg. Mass exponents suggested for the calculation of metabolic body weight of domestic cats range from 0.4 to 1, the latter exponent for the practical reason that weights of cats do not differ very much. Therefore, it is argued that a linear relationship between body weight and energy requirements leads only to a rather insignificant overestimate of the requirements of heavier cats. However, Earle and Smith (1991) showed that the heavier a cat is, the greater is the overestimate of energy requirements calculated on a body weight basis with an exponent of 1 and suggested a very low mass exponent of 0.404 based on 62 observations on DE intake. The assumption that this was not a species-specific feature of the cat but simply due to the heavier cats being fatter was made. More recent work has confirmed a lower mass exponent (Nguyen et al., 2001; Edtstadtler-Pietsch, 2003). Nguyen et al. (2001) compared ME intake, total energy expenditure, basal metabolic rate, and fat-free body mass (gas exchange monitoring and doubly labeled water method).

When only ME intake was considered, an exponent for body weight of 0.4 was obtained (Nguyen et al., 2001). When total energy expenditure was determined by the doubly labeled water method, it was related to $BW^{0.64}$ (Nguyen et al., 2001). The relationship between resting energy expenditure (gas exchange monitoring) and body weight was best described by an exponent of 0.65. The allometric coefficient for lean body mass and total energy expenditure amounted to 0.89. These results are close to the mass exponent proposed by Brody et al. (1934) for interspecific and by

Heusner (1991) for intraspecific extrapolation of energy requirements. Given the results of Nguyen et al. (2001) and the relatively uniform body shape of cats of different sizes the cat might be a species for which the theoretical intraspecific allometric coefficient of 0.67 is justified.

For larger felids such as lions and tigers, it is unclear whether the intra- or interspecific mass exponent (0.67 or 0.75) should be used. McNab (1989) reported the metabolic rate of 58 kcal·kg $BW^{-0.79}$ daily for seven species of nondomestic cat ranging in size from 4 to 138 kg, but great variability was observed between species. The Margay (3.6-kg BW) required 32 kcal·kg BW^{-1} whereas the bobcat (7.9-kg BW) required 54 kcal·kg BW^{-1}. McNab (1989) attributed this variation to differences in food and climate, with carnivores from warm environments such as domestic cats having a lower metabolic rate. Considering the diversity of energy requirements of larger felids of similar body weight (Allen et al., 1995), the question of the optimal exponent to calculate metabolic body weight is of academic rather than practical interest.

Basal Metabolic Rate and Dietary Thermogenesis

Starting with Pflueger in 1899, several authors have measured metabolic rate in domestic cats using indirect calorimetry at room temperature (Table 3-6), but the thermoneutral zone for domestic cats appears to lie between 35 and 38°C (Chapter 11). Cold-induced thermogenesis must comprise an important part of the metabolic rate at room temperature. Failure to standardize conditions provides a good explanation for much of the variation in metabolic rate observed among these studies. Most of these studies have also used cats with a narrow range of body weights, which precludes any determination of the relationship of metabolic rate to body weight or surface area. There has also been no consistency among studies that have measured metabolic rate at high temperatures (Table 11-4). Currently, therefore, the BMR of domestic cats and its relationship to body weight or surface area are unknown, but the lowest measured values may provide a close approximation.

There appear to have been no studies of dietary thermogenesis in cats. Dietary thermogenesis is probably similar to that in dogs and humans (approximately 10 percent of ME). However it may be slightly higher because protein comprises a larger part of the diet and cats eat many small meals, both of which increase dietary thermogenesis in dogs (see earlier discussion).

Adult Maintenance

Attempts to determine the energy requirements of cats go back well into the middle of the nineteenth century. Siewert (2003) reviewed historical research in cats. The oldest experiment on feline energy requirements was carried out in 1852 by Bidder and Schmidt who fed ox meat to cats. They analyzed protein and fat, so that ME in the meat could be calculated. The energy intake during periods of weight constancy in a cat of about 3 kg body weight amounted to 180 kcal ME.

Data in the literature are mostly given on a body weight basis and not for metabolic body weight. The figures suggested range from 31 to 100 kcal·kg BW^{-1} (Table 3-6). There may be several explanations for the high variation. An important point is the energy evaluation used in the studies. The use of unmodified Atwater factors for processed food may lead to overestimation of ME intake. Increased awareness of animal welfare is likely to have improved in general the living conditions of laboratory cats and may thus have considerably reduced stress. Understanding of the nutritional needs of cats has improved over the last 30 years, and thus there are fewer subclinical deficiencies in laboratory cats. Palatability of cat foods has even improved over the last decades, and in consequence it is likely that the frequency of overweight in laboratory cats may have increased.

However, even if only the newer data are compared and allowances are made for possible differences as a result of the methods employed (such as confinement during gas exchange measurements), the variation in estimated energy requirements is rather high. The reasons for this are somewhat obscure. Whereas in dogs, factors such as activity level, breed, or age have clear-cut effects on energy requirements, the effects of such factors are much less obvious in cats. There is, however, a trend toward higher energy requirements in young adult males and in all cats with a body weight considerably lower than 4 kg. It can be assumed that these cats were lean, whereas it appears likely that at least some of the heavier cats were overweight. This suggests that lean body mass may play an important role. In addition, the energy requirements are given on a body weight basis, which enhances the effects of overweight on energy requirements.

The effect of neutering on energy requirements is equivocal. Some authors observed a decrease, but others did not (Table 3-6). Neutering may decrease the percentage of lean body mass, and this indirect effect may be responsible in part for changes of energy metabolism (Laeuger, 2001). Martin et al. (2001) demonstrated lower energy expenditure in neutered cats per kilogram of body weight. The energy expenditure per kilogram of lean body mass, however, did not differ between neutered and intact cats. It is likely that depending on diet, time after neutering, and physical activity, the effect of neutering on lean body mass and thus indirectly on energy requirements may be more or less marked. On the other hand, Hoenig and Ferguson (2002) observed changes in hormonal concentrations and energy requirements in cats that were fed to maintain their weight after neutering.

Taylor et al. (1995) did not observe a decrease of maintenance energy requirements with age in cats, postulating a decreased fat digestibility as one reason. This could not be

TABLE 3-6 Reported Daily Maintenance Energy Requirements of Cats

Animal Type	*n*	Age (yr)	BW (kg)	ME (kcal·kg BW^{-1}) Mean ± 2SD[a]	Reference
Results from indirect calorimetry, extrapolation from metabolic rate					
Laboratory, intact females, neutered males, relatively low-protein diet	14	3-5	3.95	31 ± 6	Radicke, 1995
Laboratory, most neutered	24	3-15	4.4	37	Stiefel, 1999
Laboratory, intact females, neutered males	14	3-5	4.16	37 ± 11	Radicke, 1995
Laboratory, intact females, neutered males	14	3-5	3.92	38 ± 13	Radicke, 1995
Laboratory, intact females, neutered males	14	3-5	3.93	39 ± 3	Radicke, 1995
Laboratory, intact males and females	4	5-6	5.83	39 ± 5	Hauschild, 1993
Laboratory, intact females, neutered males	14	3-5	3.58	39 ± 14	Radicke, 1995
Laboratory, neutered males	6	0.9	5.5	42	Laeuger, 2001
Laboratory	6	2-8	4.1	44 ± 11	Tennant, 1998
Laboratory, intact males and females	6	1.8-5	3.88	48 ± 2	Hauschild, 1993
Laboratory, intact males	6	0.9	4.8	49	Laeuger, 2001
Laboratory, intact males and females	27	1-2	3.77	50 ± 4	Hauschild, 1993
Laboratory, intact males and females	9	4.5-13	3.27	51 ± 2	Hauschild, 1993
Laboratory, intact males and females	4	3-6	3.95	51 ± 4	Hauschild, 1993
Laboratory, intact males	6	0.8	5.1	54	Laeuger, 2001
Laboratory, intact males	6	0.8	5.2	54	Laeuger, 2001
Laboratory, intact males and females	6	1-3	3.10	54 ± 8	Hauschild, 1993
Laboratory, intact females and males	13		2.5-4.9	55 ± 11	Aub et al., 1922
Laboratory, intact males and females	5	1.2-7	3.18	55 ± 3	Hauschild, 1993
Laboratory, intact females and males	5		2.8-4.2	56 ± 13	Carpenter, 1944
Laboratory, intact males and females	6	0.8-4	3.25	61 ± 4	Hauschild, 1993
Laboratory	30		1.8-3.8	70	Benedict, 1938
Laboratory, intact females and males	14			83 ± 13	Caldwell, 1931
Results from feeding experiments, weight constancy, or extrapolation to weight constancy[b]					
Laboratory	48	1-14		22-97	Taylor et al., 1995
Laboratory	7		6-6.5	37	Earle and Smith, 1991
Laboratory, cage rest, neutered females	10		3.1	40	Flynn et al., 1996
Laboratory	26		5.5-6	42	Earle and Smith, 1991
Laboratory	14	12-14	5.1	43 ± 10	Laflamme and Ballam, 2001
Laboratory	18	10-12	5.3	43 ± 14	Laflamme and Ballam, 2001
Laboratory	53		5-5.5	46	Earle and Smith, 1991
Laboratory	48		4.5-5	48	Earle and Smith, 1991
Laboratory	12	8-10	5.0	48 ± 20	Laflamme and Ballam, 2001
Laboratory	11	>14	3.8	51 ± 14	Laflamme and Ballam, 2001
Laboratory	14	6-8	5.3	52 ± 18	Laflamme and Ballam, 2001
Laboratory, neutered males	63	1-14	5.2	55 ± 24	Edtstadtler-Pietsch, 2003
Laboratory, neutered females	33	1-13	4.1	56 ± 32	Edtstadtler-Pietsch, 2003
Laboratory	24		3.5-4	59	Earle and Smith, 1991
Laboratory	5-8	1		60	Miller and Allison, 1958
Laboratory, cage rest, intact females	5		2.9	60	Flynn et al., 1996
Laboratory, caged	32		2-4	60-70	Skultety, 1969
Laboratory	36	4-6	3.9	61 ± 22	Laflamme and Ballam, 2001
Laboratory				60	Krehl et al., 1955
Pet	36	4	5.1	62 ± 30	Parkman et al., 2000
Laboratory, intact females	30	1-11	3.9	65 ± 32	Edtstadtler-Pietsch, 2003
Laboratory, intact females, neutered males	6		4	66 ± 26	Kendall et al., 1983
Laboratory	22		2.5-3	66	Earle and Smith, 1991
Laboratory	36		3-3.5	67	Earle and Smith, 1991
Laboratory, intact males	4	3-10		67 ± 28	Edtstadtler-Pietsch, 2003
Laboratory	8	2-4	3.6	69 ± 2	Laflamme and Ballam, 2001
Laboratory, opportunity to exercise in runs				80-90	Miller and Allison, 1958
Laboratory, intact males	7	1		100 ± 52	Edtstadtler-Pietsch, 2003
Doubly labeled water					
Laboratory, neutered males	9	3.7		50	Nguyen et al., 2000
Laboratory, neutered females	6			53	Nguyen et al., 2000
Laboratory, neutered males	6	1.3		55	Nguyen et al., 2000

TABLE 3-6 continued

Animal Type	*n*	Age (yr)	BW (kg)	ME (kcal·kg BW^{-1}) Mean ± 2SD[a]	Reference
Laboratory	3	7 ± 4	4.4	55 ± 2	Ballevre et al., 1994
Laboratory	14		3.5-4.2	55	Burger et al., 1984
Laboratory, intact females	6			57	Nguyen et al., 2000
Laboratory, intact males, lean	6	2-3		59	Nguyen et al., 2000
Laboratory, intact females	12	2-3		57 ± 4	Martin et al., 2001
Laboratory, neutered females, overweight[c]	9	2-3		51 ± 4	Martin et al., 2001
Laboratory, intact males	11	2-3		57 ± 4	Martin et al., 2001
Laboratory, neutered males, overweight[c]	10	2-3		50 ± 4	Martin et al., 2001

NOTES: Includes lean as well as overweight cats. SD = standard deviation.

[a]95% of the population is within this range. Figures may be taken from graphs, SD may be estimated from variation of energy requirements per cat per day.

[b]ME of food predicted or determined by digestion trials and nitrogen correction.

[c]Neutered females were about 300 g heavier than intact females, and neutered males were 400 g heavier than intact males.

reproduced in another study (Waldrou, 2002). In contrast, Laflamme and Ballam (2001) describe a decrease of maintenance energy requirements with age. The reason for this discrepancy may be that the effect of age on maintenance requirements may be superimposed by the effect of being overweight. Old cats are less often overweight than are middle-aged cats (Scarlett et al., 1994). Edtstadtler-Pietsch (2003) saw no effect of age on maintenance energy requirements in a population of 138 laboratory cats. When the data were divided into heavy and light cats, there was a decline of energy requirements with age in both groups.

For lean cats, the energy requirements are estimated to be around 100 kcal ME·kg $BW^{-0.67}$ (Table 15-11). This translates to 70 kcal·kg BW^{-1}. This recommendation is valid only for lean cats with a body condition score (BCS) of 5 or lower on a scale of 1 to 9 (see Table 3-7). In overweight cats (BCS > 5), use of the exponent 0.4 may be justified for actual body mass (requirements 130 kcal·kg $BW^{-0.4}$). At present, the individual energy requirements of a cat cannot be more than an educated guess.

On the basis of metabolic body weight (regardless of the mass exponent), the energy requirements of exotic cats (Table 15-11) may be considerably higher. They varied enormously among feline species even if the enclosures did not permit high levels of activity (Allen et al., 1995). The range of energy intake as well as its variation are confirmed by recent unpublished data of the Wildlife Conservation Society (personal communication).

Illness and trauma can affect energy requirements dramatically. Severe illness or trauma may even double the energy requirements (Donoghue, 1991). However, these data are primarily from human patients. The experiments of Skultety et al. (1969), which were carried out to determine the effects of hypothalamic and midbrain lesions on caloric intake in cats, showed that cats with such experimentally induced lesions not only eat more food than before surgery but also maintain their weight. The intake of energy increased by 50 to 100 percent, which matches the figure given by Donoghue (1991) for severe head trauma. Watanabe et al. (1998) described a 20 percent increase of oxygen consumption in kittens after pyrogen administration.

Gestation

The pattern of weight changes during gestation and lactation appears to differ considerably between bitches and queens. Queens tend to lose body weight during lactation regardless of their diet (Scott, 1968; Loveridge, 1986; Loveridge and Rivers, 1989; Zottmann, 1997; Hendriks and Wamberg, 2000). For satisfactory reproductive performance, body weight gain in pregnancy should include net tissue accretion in preparation for lactation, rather than gain only in fetal, placental, and associated tissue weight. Figure 3-4 shows a comparison of the weight development during pregnancy and lactation in queens and bitches. Based on the results of Loveridge (1986), feeding for a 40 to 50 percent weight increase during pregnancy is recommended. Recommendations for energy intake during pregnancy based on Atwater ME intake of pregnant cats range around 140 kcal·kg $BW^{-0.67}$ (Scott, 1968; Smith, 1974; Loveridge, 1986). Since Atwater ME overestimates the ME content of prepared cat foods (NRC, 1986), it is likely that the recommendations for pregnant cats based on the above-mentioned investigations should include a considerable safety margin. Queens with a below-average maintenance energy requirement may eat less and achieve a satisfactory weight gain to prepare them for weight losses during lactation

Lactation

Queens suckle their kittens in general for 7-9 weeks, depending on litter size. Additional feeding of kittens may be started at 2½ weeks of age at the earliest and should begin during week 4 of lactation at the latest. At that age, the quantity and nutrient content of the milk are no longer sufficient for normal development (Hendriks and Wamberg, 2000).

TABLE 3-7 Body Condition Scoring System[a]

BCS	Dogs	Cats
1	Ribs, lumbar vertebrae, pelvic bones, and all bony prominences evident from a distance. No discernible body fat. Obvious loss of muscle mass	Ribs visible on shorthaired cats; no palpable fat; severe abdominal tuck; lumbar vertebrae and wing of ilia obvious and easily palpable
2	Ribs, lumbar vertebrae, and pelvic bones easily visible. No palpable fat. Some evidence of other bony prominence. Minimal loss of muscle mass	Shared characteristics of BCS 1 and 3
3	Ribs easily palpated and may be visible with no palpable fat. Tops of lumbar vertebrae visible. Pelvic bones becoming prominent. Obvious waist and abdominal tuck	Ribs easily palpable with minimal fat covering; lumbar vertebrae obvious; obvious waist behind ribs; minimal abdominal fat
4	*Ideal:* Ribs easily palpable, with minimal fat covering. Waist easily noted, viewed from above. Abdominal tuck evident	Shared characteristics of BCS 3 and 5
5	*Ideal:* Ribs palpable without excess fat covering. Waist observed behind ribs when viewed from above. Abdomen tucked up when viewed from side	*Ideal:* Well proportioned; waist observed behind ribs; ribs palpable with slight fat covering; abdominal fat pad minimal
6	Ribs palpable with slight excess fat covering. Waist is discernible viewed from above but is not prominent. Abdominal tuck apparent	Shared characteristics of BCS 5 and 7
7	Ribs palpable with difficulty, heavy fat cover. Noticeable fat deposits over lumbar area and base of tail. Waist absent or barely visible. Abdominal tuck may be absent	Ribs not easily palpable with moderate fat covering; waist poorly discernible; obvious rounding of abdomen; moderate abdominal fat pad
8	Ribs not palpable under very heavy fat cover or palpable only with significant pressure. Heavy fat deposits over lumbar area and base of tail. Waist absent. No abdominal tuck. Obvious abdominal distension may be present	Shared characteristics of BCS 7 and 9
9	Massive fat deposits over thorax, spine, and base of tail. Waist and abdominal tuck absent. Fat deposits on neck and limbs. Obvious abdominal distension	Ribs not palpable under heavy fat cover; heavy fat deposits over lumbar area, face, and limbs; distension of abdomen with no waist; extensive abdominal fat deposits

[a]Based on Laflamme, 1997a,b.

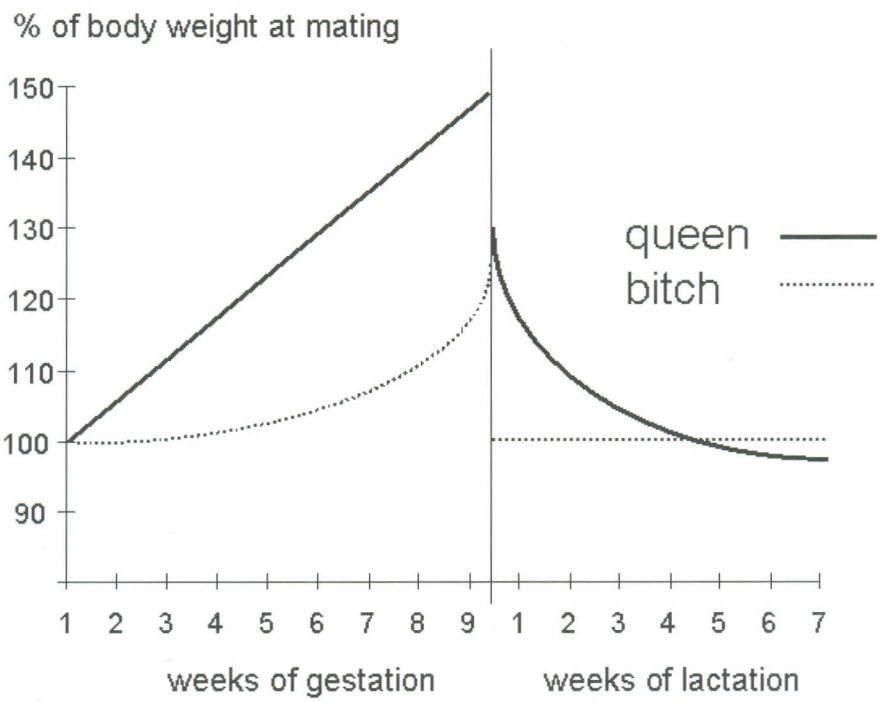

FIGURE 3-4 Schematic comparison of body weight changes of queen and bitch during gestation and lactation (data from Meyer et al., 1985a,b; Loveridge, 1986).

Milk yield and energy content in milk are important factors in estimating the energy requirements for milk production. Compared to dogs, data on milk yield for queens are rather scarce. Milk yield of queens depended strongly on the number of kittens and the stage of lactation (Dobenecker et al., 1998). Milk yield increased after parturition until the third or fourth week of lactation and decreased again thereafter. Dobenecker et al. (1998) used the method of weighing kittens before and after suckling, a method that tends to underestimate milk yield. They did not determine milk intake of the kittens every day but gave them breaks in between. They compared the weight gain of kittens on those days when they remained with their queen all the time and were only weighed once and on other days when they were parted from the queen and weighed before and after suckling. Based on the differences in weight development of kittens, the extent of the error was estimated to amount to about 20 percent. The milk yield of cats was corrected accordingly and was estimated to range between 1.5 and 8 percent of body weight at the peak of lactation. The milk yield of queens with one or two kittens remained below 2 percent of body weight. Queens with three or four kittens had a milk yield of 5-6 percent, and a maximum of 8 percent was observed in a queen with six kittens. The estimate of Dobenecker et al. (1998) agrees very well with newer results of Hendriks and Wamberg (2000) who used isotope dilution techniques. In five queens with three or four kittens each, milk yield averaged 5.1, 5.5, 6.1, and 6.0 percent of body weight during the first 4 weeks of lactation, respectively. In the first week of lactation, however, the milk yield measured by Dobenecker et al. (1998) was lower than the milk yield determined by Hendriks and Wamberg (2000) who used isotope dilution technique. It is likely that the frequent interference with the kittens when estimating milk yield by weighing before and after suckling had more marked effects in the first week of life than later. Both studies agree that peak lactation is in the third or fourth week of lactation. It can be estimated from these studies that in the 1st week of lactation milk yield is about 85 percent of peak lactation, in the 2nd week it is 95 percent in the third and fourth 100 percent, and thereafter decreases to 85, 75, and 60 percent in weeks 5, 6, and 7, respectively.

Energy content of queens' milk increases gradually during lactation from about 1 to 1.3 kcal·g^{-1} milk (Keen et al., 1982; Zottmann, 1997). Consequently, the energy losses in milk increase more during the first 4 weeks and decrease less rapidly later on than the milk yield does. For factorial calculation of net metabolic need for milk production, weekly changes of milk energy content and milk yield, as well as the effect of litter size on milk yield, were taken into account. Energy losses in milk were calculated separately for small (one to two kittens), medium (three to four kittens), and large (more than four kittens) litters for each week of lactation. Then the mean was calculated, and each week was compared to the mean. The resulting factors for the stage of lactation in the equation for calculating the requirements of lactating cats take into account both milk yield and changes in energy content of the milk.

For a factorial calculation of energy requirements for milk production from the energy output in milk (Kienzle, 1998), an estimate of utilization of ME for milk production is needed. However, there are no data for cats. Based on information from other species, utilization can be assumed to range around 60 to 70 percent. The dog is likely to be the best model because the diet of cats is more similar to that of dogs than to diets of other domestic species. The work of Scantlebury et al. (2000) demonstrates the lower range of utilization of energy for milk production in dogs. Therefore, energy output by milk was divided by 60 and multiplied by 100 to calculate energy requirements for milk yield in cats.

Maintenance requirements are added to the requirements for milk yield. A queen rearing a litter can be assumed to be rather active and will become lean with progressing lactation. Therefore, the equation for maintenance requirements of lean cats was chosen to calculate this part of the requirements (100 kcal·kg BW$^{-0.67}$).

By adding the maintenance energy requirements and the energy requirements for milk production, figures for total requirements are obtained that are much higher than the energy intake in feedings experiments (Loveridge, 1986; Zottmann, 1997; Hendriks and Wamberg, 2000). As mentioned above, after parturition, cats are heavier than before mating and they normally lose weight during lactation. These weight losses (i.e., the energy available from extra genital tissues gained during gestation) have to be considered for factorial calculations. The average weight loss during lactation amounts to 700 to 800 g (Loveridge and Rivers, 1989; Zottmann, 1997; Hendriks and Wamberg, 2000). Allowing for considerable individual variation, a daily weight loss of 5 g (small litters) to 20 g (medium and large litters) was assumed for factorial calculations. It was further assumed that the majority of the lost tissue was fat and that this was utilized very efficiently. One gram of weight loss would yield 7-8 kcal ME. In a cat with a 3-kg body weight, a weight loss of 20 g would then translate to 50 kcal ME·kg BW^{-1}·d^{-1} from using body stores (and a weight loss of 5 g, to about 12 kcal·kg BW^{-1}, respectively). For queens nursing litters with more than four kittens, 50 kcal·kg BW^{-1} was subtracted from the factorially calculated requirements; for queens with three to four kittens, only 40 kcal·kg BW^{-1} was substracted; and for queens with less than three kittens, an even smaller subtraction was made because they are likely to lose less weight during lactation than queens with larger litters. The results of these calculations are given in Table 15-13. Individual differences in tissue breakdown during lactation are likely to occur but cannot be taken into account. This makes the above calculations appear rather academic. As a rule of thumb, the energy requirement of a lactating queen with more than two kittens amounts to between 2 and 2.5 times the maintenance requirements of the queen at mat-

ing. Lactating queens should be fed a highly palatable food with at least 4 kcal ME·g^{-1} dry matter, and they should have free access to their food.

Growth

The publications available on energy intake of growing kittens were reviewed (Allison et al., 1956; Miller and Allison, 1958; Waterhouse and Carver, 1962; Greaves, 1965; Loveridge, 1987; Kienzle 1989; Munday et al., 1991; Iben and Sadila, 1993; Zottmann, 1997; Hendriks and Wamberg, 2000). In addition, a factorial calculation of requirements for growth was carried out using the data from Stratmann (1988). For newborn suckling kittens, an energy requirement of about 20-25 kcal per 100 g of body weight was estimated. For calculation of requirements after weaning, the data were pooled and an equation was derived to estimate energy requirements for growth from actual body weight and expected mature weight (Table 15-9). The data used for the calculations include a number of errors. For example, older publications used Atwater ME and consequently tended to overestimate ME intake. When milk intake of kittens was determined by weighing before and after suckling or when diets were fed that were not very palatable, there could be an underestimate. A systematic deviation of a majority of data into either over- or underestimation, however, is unlikely. Nevertheless, the equation was checked against data on growth and energy intake (week 10 to week 19; Edtstadtler-Pietsch, 2003) and the agreement was satisfactory.

ENERGY DEFICIENCY AND EXCESS IN DOGS AND CATS

Signs of energy deficiency are frequently nonspecific, and diagnosis may be complicated by a simultaneous shortage of several nutrients. The most conspicuous and reliable sign of uncomplicated energy deficiency is a generalized loss of body weight. Under conditions of partial or complete starvation, most internal organs exhibit some atrophy. A loss of subcutaneous, mesenteric, perirenal, uterine, testicular, and retroperitoneal fat is an early sign. Low fat content of the marrow in the long bones is a good indicator of prolonged inanition. Brain size is least affected, but the size of gonads may be greatly decreased. Hypoplasia of lymph nodes, spleen, and thymus leads to a marked reduction in their size. The adrenal glands are usually enlarged. The young skeleton is extremely sensitive to energy deficiency, and growth may be slowed or stopped completely. In the adult, the skeleton may become osteoporotic. Lactation and the ability to perform work are also impaired. As muscle proteins are catabolized for energy, endogenous nitrogen losses increase. Parasitism and bacterial infections frequently occur under such circumstances and may superimpose other clinical signs.

Excess energy leads to overweight or even obesity. All body fat stores increase in size. Obesity is statistically or causally linked to a number of diseases such as diabetes mellitus (Lutz and Rand, 1993). It may enhance the severity of other diseases such as skeletal or heart problems as well as the risk of hyperlipidemia in cats. In growing animals, excess energy intake may induce excessive growth rates. In puppies from large breeds, this has been repeatedly associated with the onset or enhancement of developmental skeletal disease (Hedhammar et al., 1974; Kealy et al., 1992; Meyer and Zentek, 1992). A recent study in dogs demonstrated that overfeeding from weaning to old age considerably impairs health and longevity (Kealy et al., 2002). In this study, osteoarthritis was a special problem in overfed dogs (Kealy et al., 1997, 2000).

Body Condition

Ideally, body condition can be assessed by determining body fat content by various indirect methods. The results may differ somewhat from direct measurement in the body as carried out by Stadtfeld (1978) for dogs and by Stratmann (1988) and Hendriks et al. (1997) for cats. In adult dogs, mean body fat content (acid-ether extract) was 23 percent (Stadtfeld, 1978) and water content was 56 percent. In relatively lean cats, fat content was somewhat lower (11-12 percent) and water content higher (62 percent; Hendriks et al., 1997; Stratmann, 1988). A simple and practical way to assess body condition is the use of body condition scoring systems (Table 3-7), which rely mainly on the palpation of subcutaneous fat deposits. There are two systems with scores between 1 (emaciated) and 5 (obese) and between 1 (emaciated) and 9 (obese). The advantage of a system using 9 scores (Table 3-7) is that there is no need for "half" points. It is recommended to keep BCS (system with 9 scores) within the range of 4 to 5 in dogs. In cats, 5 is assumed to be ideal.

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4

Carbohydrates and Fiber

DEFINITION, CLASSIFICATION, AND MEASUREMENT

Dietary carbohydrates include low and high molecular weight sugars, starches, and various cell wall and storage non-starch polysaccharides (NSPs) or dietary fibers (DFs) (Bach-Knudsen, 1997) produced by plants during photosynthesis (Hassid, 1970). Carbohydrates $[C_n(H_2O)_n]$ have hydroxyl groups and are markedly hydrophilic (Lichtenthaler, 1998). They are the primary energy source for omnivorous animals (Guilbot and Mercier, 1985) and can be separated into distinct groups depending on their degree of polymerization (DP) and digestibility (Nantel, 1999). The four carbohydrate groups, from a functional perspective, are absorbable (monosaccharides), digestible (disaccharides, certain oligosaccharides, and nonstructural polysaccharides), fermentable (lactose, certain oligosaccharides, DF, and resistant starch), and nonfermentable (certain DFs). Carbohydrates may fall into two or more different groups depending on animal species and age, food processing characteristics, or amount of feed ingested.

Absorbable Carbohydrates

Absorbable carbohydrates include monosaccharides (glucose, fructose, and galactose; Hassid, 1970) and sugar alcohols (sorbitol, mannitol, and xylitol; BeMiller and Whistler, 1996). These compounds can be absorbed directly and, therefore, do not require hydrolysis by gastric enzymes.

The measurement of monosaccharides and sugar alcohols is achieved by extracting the simple sugars from a feed or food sample with 80 percent ethanol and quantifying the low molecular weight sugars in the supernatant by gas-liquid chromatography (GLC), high-performance liquid chromatography (HPLC) with either pulsed amperometric detection (PAD) or pulsed electrochemical detection (PED), or capillary electrophoresis (CE). The total monosaccharides of a sample reflect the carbohydrate concentration, which complements assays for oligosaccharides, starch, and NSPs (Harris et al., 1988; Piccaglia and Galletti, 1988).

Digestible Carbohydrates

Disaccharides have two monomeric residues and include lactose, sucrose, maltose, and trehalose. These low molecular weight sugars are readily hydrolyzable by gastrointestinal tract enzymes. It is important to note, however, that under certain conditions, lactose absorption in the small intestine is reduced. Unabsorbed lactose is readily fermented in the colon.

Starch is a nonstructural plant storage polysaccharide (α-glucan) (Englyst, 1989) and is the main carbohydrate in cereal grains (Bach-Knudsen, 1997). Dietary starch is composed of amylose (linear glucose chain with α-1,4-glucosidic linkages) and amylopectin (branched glucose polymer containing both α-1,4- and α-1,6-linkages).

The primary method of starch quantification (McCleary et al., 1994) is an enzymatic, colorimetric total starch determination. Other methods for the classification and measurement of starch also have been described (Thivend et al., 1972; Aman and Hesselman, 1984; Karkalas, 1985; Holm et al., 1986; Englyst et al., 1992a, b).

Fermentable Carbohydrates

Oligosaccharides are polymeric carbohydrates consisting of three to ten monosaccharide residues joined through glycosidic bonds (Pazur, 1970). Lee and Prosky (1994, 1995, 1999) classified oligosaccharides that were not digested by endogenous digestive enzymes as resistant oligosaccharides. Some nondigestible oligosaccharides include inulin-type fructans, galactooligosaccharides, lactulose, isomaltooligosaccharides, xylooligosaccharides, fructooligosaccharides, raffinose, and stachyose. Certain oligosaccharides can be classified as prebiotics. Prebiotics

are nondigested food ingredients that beneficially affect the host by stimulating the growth and activity of one or a limited number of bacterial species already residing in the colon (Gibson and Roberfroid, 1995; Grizard and Barthomeuf, 1999), and also are defined as functional foods (Van Loo et al., 1999). Oligosaccharides are extracted and quantified using several methods such as GLC, HPLC-PAD, or HPLC-PED (Quigley and Englyst, 1992; Englyst et al., 1994; Campbell et al., 1997) and computer-assisted spectrum evaluation of polysaccharides (CASPER) (Stenutz et al., 1998).

The activity of lactase in the small intestine of adult dogs and cats is much lower than in juvenile animals, while sucrase levels are low in both species throughout life and are influenced by diet composition (Welsh and Walker, 1965; Kienzle, 1993d). Therefore, lactose and sucrose may escape digestion by endogenous enzymes and be fermented in the large intestine. These then can be considered resistant disaccharides, as well as fermentable carbohydrates (Kienzle, 1989).

Starch and products of starch degradation that escape digestion and absorption in the small intestine are termed resistant starch (RS) (Englyst, 1989; Muir and O'Dea, 1993) and may be fermented by hindgut bacteria to varying extents (Gee et al., 1992; Murray et al., 1998, 2001). Resistant starch can be classified into four categories: physically inaccessible, resistant starch granules, retrograded starch, or chemically modified starch (Lineback, 1999; Bird et al., 2000). If RS is included in the measurement of NSP, the proportion of NSP-glucose in heat-processed starchy foods becomes inflated (Englyst, 1989) because processing starchy foods can result in the production of RS (Englyst and Cummings, 1987). Methods to measure RS (Bjorck et al., 1986; Champ, 1992; Englyst et al., 1992a; Muir and O'Dea, 1993; Faisant et al., 1995; Champ et al., 1999a,b) are not without their problems. The definition of RS relies on solubility of starch as a major criterion, so there is lack of a clear definition of RS from an analytical perspective (Lineback, 1999). This problem was resolved by McCleary et al. (2002) where 37 laboratories tested eight pairs of blind duplicate starch or plant material samples for RS content. The range of applicability of the test was for samples testing between 2 and 64 percent RS. The recommendation was approved by the Methods Committee on Food Nutrition as First Action (AOAC).

The definition of dietary fiber has been the subject of much debate. Trowell (1972) defined DF as the skeletal remains of plant cells resistant to digestion by human gastrointestinal tract enzymes, and then redefined it (Trowell et al., 1976) as the remnants of edible plant cell wall polysaccharides, lignin, and associated substances resistant to hydrolysis by human alimentary tract enzymes.

Dietary fiber is composed of cell wall polysaccharides, noncellulose polysaccharides, and structural nonpolysaccharides (lignin) (Englyst, 1989; Report of the British Nutrition Foundation Task Force, 1990; Eastwood, 1992; Theander et al., 1994). These structural polysaccharides include cellulose, hemicelluloses, and some pectins, while noncellulosic polysaccharides include pectins, gums, and mucilages. Chemically, the building blocks of cell wall polysaccharides are pentoses (arabinose, xylose), hexoses (glucose, galactose, mannose), 6-deoxyhexoses (rhamnose, fucose), and uronic acids (glucuronic and galacturonic acids) (Bach-Knudsen, 1997). The main polysaccharides of plant cell walls include arabinoxylans and mixed linked $\beta(1\rightarrow3:1\rightarrow4)$-D-glucans ($\beta$-glucans), xyloglucans, xylans, rhamnogalacturonans, and arabinogalactans (Stephan, 1983; Selvendran, 1984; Theander et al., 1989).

The fiber in animal feeds and petfoods is determined by the crude fiber method (Henneberg and Strohman, 1859), total fiber method (Englyst and Cummings, 1988), neutral detergent fiber (NDF) method (Roberston and Van Soest, 1981; Van Soest, 1963; Van Soest et al., 1991), total dietary fiber (TDF) method (Prosky et al., 1984), nonstructural polysaccharide method (Englyst et al., 1992b), and several other methods (Asp et al., 1983; Englyst and Hudson, 1987; James and Theander, 1981; Prosky et al., 1984; Roberston and Van Soest, 1981; Southgate, 1981; Theander and Westerlund, 1986; Prosky, 1991). These methods can be categorized as gravimetric or chemical analyses (Marlett, 1989). Gravimetric methods do not provide information about the nature and composition of the fiber or NSP, and tend to omit the analysis of certain DF components. For example, the TDF procedure (Prosky et al., 1984) fails to recover and measure lower molecular weight saccharides such as fructooligosaccharides (Gordon, 1999). The crude fiber method accounts for only 5 to 20 percent of the total fiber in a food and, as such, underestimates the true DF concentration (Bartges and Anderson, 1997). In contrast, chemical analysis methods determine the sugar constituents by HPLC, GLC, or CE, and uronic acids colorimetrically. Chemical analyses estimate DF as the sum of monosaccharides released by the hydrolysis of NSP, leading to a more thorough assessment of DF content (Englyst and Cummings, 1984; Englyst et al., 1982, 1987; Englyst and Hudson, 1987; Englyst, 1989; Marlett, 1989). Uronic acid constituents of NSP can be determined by HPLC-PAD (Quigley and Englyst, 1994). High-performance anion exchange chromatography (HPAEC) with either PAD or PED is increasingly being advocated as a suitable method to analyze DF and complex carbohydrates in foods and feeds (Piccaglia and Galletti, 1988; Henshall, 1999) but is more costly and time-consuming than gravimetric analytical methods.

Novel analytical procedures enable more exact and accurate characterization of fibrous carbohydrate constituents and lignin and provide impetus for in-depth study and better understanding of nutritional, physiological, health, and immunological implications of carbohydrates in petfoods. Therefore, crude fiber analysis of petfoods should be replaced by a more physiologically relevant method. Methods

such as TDF or HPAEC accurately isolate and quantify dietary fiber, and are capable of separating soluble and insoluble fiber fractions.

Nonfermentable Carbohydrates

Certain dietary fibers are not extensively fermented by microbiota present in the gastrointestinal tract of dogs and cats. Cellulose and wheat bran are examples of nonfermented carbohydrates. Although lignin is a polyphenolic compound, it generally is grouped with the carbohydrate components of nonfermentable DF. These compounds contribute directly to fecal bulking and reduce intestinal transit time.

Lignin can be determined via the acid detergent lignin or Klason lignin methods (Van Soest, 1963; Van Soest and Wine, 1967; Theander and Westerlund, 1986). Cellulose can be determined indirectly by calculating the difference between acid detergent fiber (ADF) (cellulose and lignin) and acid detergent lignin residues (Van Soest, 1963), or directly by using the method of Crampton and Maynard (1938).

ABSORBABLE CARBOHYDRATES (MONOSACCHARIDES AND SUGAR ALCOHOLS)

Presence in Foodstuffs

Glucose and fructose are the predominant free-occurring monosaccharides in dog and cat foods. Cereal and legume grains, their by-products, and other plant components are the main sources of monosaccharides in petfoods. Table 13-1 (Chapter 13) lists carbohydrate fraction (including monosaccharide) concentrations in plant ingredients commonly used in the preparation of dog and cat foods.

Sugar alcohols (also known as polyols) also are present in nature but are more commonly synthesized by hydrogenating a reducing monosaccharide (Lichtenthaler, 1998). Sorbitol is produced from glucose, mannitol from mannose, and xylitol from xylose (BeMiller and Whistler, 1996).

Digestion, Absorption, and Utilization

Free monosaccharides and sugar alcohols are absorbed directly and, therefore, do not require digestive enzymes. Only monosaccharides present as constituents of carbohydrate polymers require hydrolytic enzymes in order to be absorbed in the small intestine.

In both dogs and cats (similar to many other species), absorption of glucose and galactose across the brush border membrane occurs mainly by an active Na^+-dependent transport mechanism in addition to uptake by Na^+-independent simple diffusion (Washabau et al., 1986; Wolfram et al., 1989). Fructose is an exception, being absorbed by a Na^+-independent glucose transporter system (GLUT-5) in humans (Levin, 1994) and likely in companion animals as well.

Using the breath hydrogen test in dogs, Washabuau et al. (1986) found dietary glucose to be completely absorbed. Levinson and Englert (1970) measured in vivo transport of D-glucose, D-galactose, and D-xylose in cat jejunum. With increasing sugar concentration (from 1 to 40 mM/L), there was increased transport of D-glucose (from 3.2 ± 1.6 to 37.0 ± 8.6 $\mu M \cdot h^{-1} \cdot g^{-1}$ wet tissue weight), D-galactose (from 3.0 ± 0.6 to 40.0 ± 10.5 $\mu M \cdot h^{-1} \cdot g^{-1}$ wet tissue weight), and D-xylose (from 1.1 ± 0.6 to 19.5 ± 4.8 $\mu M \cdot h^{-1} \cdot g^{-1}$ wet tissue weight). Both Kienzle (1994) and Morris et al. (1977) reported that glucose and galactose in cat foods are nearly 100 percent absorbable. Galactitol was found in the urine of cats fed a diet containing 39 percent galactose (Kienzle, 1989).

In humans, glucose is the main metabolite of carbohydrate digestion that enters intermediary metabolism (Jequier, 1994) and is disposed of by direct oxidation or utilization in various tissues (Flatt, 1988), including glycogen synthesis in the liver and muscles (Ebiner et al., 1979) and lipid synthesis (Flatt et al., 1985). Glucose provides energy and supplies carbon skeletons for biosynthesis of other compounds in the dog as well (Hilton, 1990). As in humans, there is probably an obligatory requirement for glucose in organs such as the brain of the dog. In the absence of dietary glucose, dogs synthesize glucose from amino acids and glycerol by way of gluconeogenesis (Belo et al., 1976; Romsos et al., 1976).

The fact that cats are in a constant state of gluconeogenesis (Kienzle, 1993b,c) implies that glucose is important for normal metabolism in the feline species. However, they do not appear to utilize carbohydrates as rapidly as do dogs. Cats have comparatively longer blood glucose elimination times (Mansfield et al., 1986; Kienzle, 1994). Furthermore, Kienzle (1994) observed galactosemia and galactosuria in healthy adult cats fed diets containing 39 percent galactose (dry matter [DM] basis).

Sugar alcohols are absorbed via passive diffusion in the human small intestine (Finley and Leveille, 1996) and, therefore, are absorbed to a much lesser extent than their monosaccharide counterparts. Sorbitol is 50 percent absorbed, while mannitol and xylitol are approximately 25 percent absorbed (Finley and Leveille, 1996). Dogs fed diets containing 20 percent sorbitol or xylitol grew similarly to dogs fed diets containing 20 percent sucrose. However, dogs fed diets containing 20 percent sorbose lost weight (Keller, 1980). Unabsorbed sugar alcohols are fermented by colonic microflora. No data are available on the specific utilization of sugar alcohols by companion animals.

Factors Affecting Digestibility, Absorption, and Utilization

Digestibility or absorption of monosaccharides is influenced by carbohydrate source and fraction (Bach-Knudsen and Hansen, 1991), processing conditions (Marsman et al., 1997), interactions of monosaccharides with other dietary components, and physiological state of the animal.

Quantities of monosaccharides in companion animal diets also influence their digestibility or absorption. Levinson and Englert (1970) determined that increasing concentrations of monosaccharides infused into the cat small intestine resulted in increasing rates of absorption. However, Buddington et al. (1991) reported that cats are unable to upregulate intestinal glucose or fructose transporter activity in response to changes in dietary carbohydrate level. Presumably, very high doses of monosaccharides may exceed the absorptive capacity of the small intestine. This is especially true for xylose, which is absorbed via passive diffusion, and is poorly absorbed by dogs (Washabau et al., 1986). These unabsorbed monosaccharides would be available for fermentation in the large intestine. As a result of colonic fermentation, total tract digestibilities of monosaccharides by the dog are always close to 100 percent. However, even acute doses of 0.5 g glucose·kg BW^{-1} resulted in negligible breath hydrogen gas production in dogs (Washabau et al., 1986), suggesting efficient glucose absorption.

Glucose utilization may be impacted by diet macronutrient composition. Belo et al. (1976) found that dogs fed 62 percent carbohydrate-25 percent protein diets exhibited higher rates of glucose utilization (131 $g \cdot d^{-1}$) per dog than those consuming a 27 percent carbohydrate-46 percent protein diet (84 $g \cdot d^{-1}$ per dog). This closely matched the amount of carbohydrate consumed per dog (137 $g \cdot d^{-1}$ for the former group and 56 $g \cdot d^{-1}$ for the latter group). Dogs consuming carbohydrate-free diets exhibited the lowest rates (60 to 80 $g \cdot d^{-1}$ per dog) of glucose utilization. This suggests that dogs can alter their metabolic fuel sources depending on nutrient availability but possess a certain minimal metabolic requirement for glucose, regardless of diet composition. Cats likely have lower rates of glucose utilization, since they have lower levels of glucokinase activity, a hepatic enzyme that in other species is adaptive to diet and blood glucose levels (Ballard, 1965). Drochner and Muller-Schlosser (1980) and Kienzle (1989) reported glucosuria in cats consuming a 25 percent glucose diet. Thus, even though cats may absorb dietary carbohydrates well, the rate of utilization of the resulting glucose likely is much less efficient.

Nutritive Value

The nutritive value of monosaccharides in dog diets is a product of digestibility, absorption rate, and quantity present. Dietary monosaccharides are oxidized to provide tissue energy. The heat of combustion (gross energy) of glucose is 3.75 $kcal \cdot g^{-1}$ (15.7 $kJ \cdot g^{-1}$) (Jequier, 1994). One mole of glucose is anaerobically metabolized through the glycolytic pathway to 2 moles of adenosine triphosphate (ATP). However, complete aerobic oxidation of 1 mole of glucose yields 38 moles of ATP in humans. Since dogs and cats utilize similar metabolic pathways to humans, similar energy values likely exist. Sugar alcohols have much lower energy values than monosaccharides. Sorbitol contains 1.80 to 3.30 $kcal \cdot g^{-1}$ (7.53 to 13.81 $kJ \cdot g^{-1}$) of metabolizable energy, while mannitol provides approximately 1.60 $kcal \cdot g^{-1}$ (6.70 $kJ \cdot g^{-1}$) and xylitol contains approximately 2.40 $kcal \cdot g^{-1}$ (10.05 $kJ \cdot g^{-1}$) metabolizable energy (Finley and Leveille, 1996).

Physicochemical Effects

Table 4-1 summarizes information available on physicochemical and physiological effects of the four carbohydrate groups, as well as health-related characteristics that may be attributed to them as a result of their consumption by dogs and cats. Each is discussed briefly in subsequent sections.

Osmotic Effects

Monosaccharides increase osmolality more than disaccharides such as lactose, and their presence in high concentrations may result in diarrhea in newborn animals (Debraekeleer, 1998). Unabsorbed monosaccharides induce fluid secretion into the small intestinal lumen via osmosis. This, in combination with the rapid colonic fermentation of unabsorbed sugars, results in reduced transit time (Washabau et al., 1986). Although monosaccharides have a more potent influence on osmosis, osmotic effects of disaccharides are more commonly observed under practical conditions because of their ability to escape digestion and absorption in the small intestine. For diets containing lactose and sucrose, higher water content has been observed in the chyme of the small and large intestine, as well as in feces (Kienzle, 1989; Meyer et al., 1989). In addition, Meyer et al. (1989) described a higher ileocecal water flow.

Physiological Effects

Effects on Food Intake, Transit Time, and Fecal Excretion

Few data are available evaluating the effects of absorbable carbohydrates on food intake. Kienzle et al. (1993c) reported that acceptance of meat-based diets supplemented with 38.7 percent glucose was similar to the carbohydrate-free control diet. However, the 38.7 percent galactose diet resulted in only one-third the food intake compared to the glucose diet. Similarly, Morris et al. (1977) reported that meat-based cat diets supplemented with glucose (7:1 w/w) were consumed at a level similar to the basal meat-based diet.

In the cat, Kienzle (1993c) found that dietary disaccharides altered fecal pH, but fecal pH was unaffected by dietary glucose (7.15), galactose (6.96), or a carbohydrate-free diet (7.22), and that dietary sugars altered fecal concentrations (millimoles per kilogram of feces, wet weight) of short-chain fatty acids (SCFAs) (124 ± 35, $n = 11$, for a 38.7 percent galactose diet; 95 ± 27, $n = 9$, for a 38.7 percent glucose diet; 307 ± 139, $n = 20$, for a carbohydrate-free diet

TABLE 4-1 Summary of Physicochemical, Physiological, and Health-Related Effects of Absorbable, Digestible, Fermentable, and Nonfermentable Carbohydrates in Dog and Cat Nutrition

	Carbohydrate Class			
Item	Absorbable	Digestible	Fermentable	Nonfermentable
Physicochemical effects				
Osmotic	√	√	√	NI
Water binding capacity	NI	NI	√	√
Viscosity	NI	√	√	√
Bulking	NI	NI	√	√
Physiological effects				
Food intake	NI	√	√	√
Transit time	NI	NI	√	√
Fecal excretion	√	NI	√	√
Nutrient availability	NI	√	√	√
Growth performance	NI	√	NI	√
Reproductive performance	√	√	√	NI
Weight control	NI	√	√	√
Geriatric nutrition	NI	NI	NI	NI
Health-related effects				
Gastrointestinal health	NI	√	√	NI
Glycemic control	√	√	√	NI
Immune function	NI	NI	√	NI

Abbreviations used: √ = published information available; NI = no information available.

containing 21.8 percent fish oil). Furthermore, fecal dry matter percentage was increased in cats consuming glucose- or galactose-containing diets compared to those consuming a carbohydrate-free diet (61.4 and 60.7 vs. 52.5 percent fecal dry matter for glucose, galactose, and carbohydrate-free diets, respectively).

Effects on Reproductive Performance

The need for carbohydrates in pregnant and lactating bitches appears to depend on the protein concentration in the diet. Romsos et al. (1981) reported that a carbohydrate-free diet resulted in a smaller litter size in beagles than when bitches were fed a diet containing corn starch. In the carbohydrate-free diet, 26 percent of the calories came from protein and 74 percent from fat. Kienzle et al. (1985) fed carbohydrate-free diets with different concentrations of protein to pregnant and lactating bitches. In bitches fed the high-protein, carbohydrate-free diet (42 percent of calories from protein), litter size, birth weight, and puppy survival rate were comparable to those when bitches were fed a carbohydrate-containing control diet. In contrast, in bitches fed the low-protein, carbohydrate-free diet (20 percent of calories from protein), a reduction in birth weight (30 to 40 percent) and an increase in perinatal mortality rate (75 percent) were observed, which was more severe than was reported in the study of Romsos et al. (1981). These data indicate that, although pregnant and lactating bitches do not require a dietary source of carbohydrate, they have increased protein requirements when fed a carbohydrate-free diet.

Effects in Geriatric Nutrition

Although the terms "old," "senior," and "geriatric" often are used interchangeably, they do have distinct definitions. The term "senior" refers to the functionality of an animal. An animal is considered to be senior when it decreases activity, gains weight, and develops other age-related physical and behavioral changes (Markham and Hodgkins, 1989). Conversely, the term "geriatric" refers to the chronological age of the animal. Generally, giant- and large-breed animals are considered geriatric at 5 years of age, whereas medium- or small-breed dogs and all cats are not considered geriatric until 7 or more years of age (Markham and Hodgkins, 1989).

Geriatric nutrition of dogs and cats should aim at prolonging the length and quality of life and delaying the onset of geriatric dysfunction and disease states (Burkholder, 1999). With increasing age, intestinal transit slows and basal metabolism also decreases (Barrette, 1990). Decreasing organ reserves, alterations in enzyme activity, impaired circulation, and lowered rate of absorption and excretion of nutrients are other manifestations of gastrointestinal dysfunction. Prolonged gastric emptying times also can occur as a result of decreased intestinal blood flow (Mosier, 1989). The decrease in physical activity and metabolism of aging dogs

and cats (Mosier, 1989) results in a reduction of about 20 percent in maintenance energy requirements compared to young adult animals (Harper, 1998), along with a decreased glucose tolerance (Sheffy and Williams, 1981; Mosier, 1989). The age-related decline in glucose tolerance appears to result from tissue unresponsiveness to insulin (Strasser et al., 1993). Regardless of diet, old dogs require a longer period for blood glucose concentrations to attain baseline than do young dogs (Mosier, 1989; Sheffy et al., 1985).

Adult maintenance diets for dogs contain 10 to 13.4 g per 100 kcal ME (37 to 53 percent of kilocalories per day from carbohydrate), whereas senior dog diets have 11.8 to 17.6 g per 100 kcal ME from carbohydrate, or 29 to 62 percent of kilocalories from carbohydrates (Burkholder, 1999). Conversely, adult and maintenance diets for cats contain 4.5 to 10.9 g per 100 kcal ME from carbohydrate (16 to 37 percent of kilocalories), whereas senior cat diets have 6.4 to 11.3 g per 100 kcal ME from carbohydrate, or 22 to 40 percent of total energy from carbohydrates (Burkholder, 1999).

There is a lack of scientific agreement on how aging affects glucose tolerance in companion animals. Strasser et al. (1993) found that old dogs have increased plasma glucose concentrations (97.00 ± 2.32 mg·dL^{-1}) as opposed to young dogs (91.13 ± 2.39 mg·dL^{-1}), and a decreased glucose tolerance as indicated by reduced glucose clearance rates (-1.92 ± 0.54 mg·L^{-1}·min^{-1}) compared to young dogs (-2.94 ± 0.36 mg·L^{-1}·min^{-1}). On the contrary, Fukuda et al. (1989) found no age-related change in plasma glucose concentrations of beagle dogs. Lowseth et al. (1990) reported no significant changes in blood glucose concentrations in beagle dogs aged 3 to 14 years, with the exception of significantly reduced blood glucose concentrations in 12-year-old beagles. Sheffy et al. (1985) concluded that the ability of 10- to 12-year-old dogs to utilize nutrients was no different from that of young adult dogs.

Health-Related Characteristics

Glycemic Response

Absorbed carbohydrates result in physiological responses that depend on the rate of glucose entry into intermediary metabolism and are central in the concept of the glycemic index of foods (Jenkins et al., 1981). If glucose entry into the bloodstream exceeds its removal, a postprandial rise in plasma glucose concentration ensues. The normal range of plasma glucose in dogs and cats is 70 to 120 mg·dL^{-1} (Swenson, 1989).

Dietary glucose results in a large increase in blood sugar level (glycemic index = 140), whereas fructose, which is metabolized without insulin, results in little increase (glycemic index = 30) in humans (Jenkins et al., 1981). Zentek et al. (1998) found that dogs tolerated a total parenteral nutrition (TPN) formula in which glucose provided 62.3 percent of the total dietary energy. However, they recommended intensive monitoring of glucose in dogs with disturbed glucose homeostasis.

DIGESTIBLE CARBOHYDRATES (DISACCHARIDES, CERTAIN OLIGOSACCHARIDES, AND NONSTRUCTURAL POLYSACCHARIDES)

Presence in Foodstuffs

Table 13-1 lists carbohydrate fraction concentrations in plant ingredients commonly used in the preparation of dog and cat foods. Lactose, maltose, and sucrose are the common disaccharides present in dog and cat foods. The major natural sources of oligosaccharides in dog and cat foods are cereals, legumes, and other plant ingredients.

Cereals, legumes, other plant foodstuffs, and plant by-products used in formulating dog and cat foods have different starch contents (Table 4-2). Foods low in starch (e.g., corn gluten feed, 190 g·kg^{-1} DM) generally contain more fiber or non-starch polysaccharides, whereas starch-rich foods (corn starch, 630 g·kg^{-1} DM) generally contain less fiber.

Digestion, Absorption, and Utilization

Disaccharides are degraded to their monomers (e.g., lactose to glucose and galactose; sucrose to glucose and fructose; maltose to two glucose units) before absorption. The

TABLE 4-2 Starch Content of Some Starch-Rich Foodstuffs and By-products Used in Dog and Cat Foods

Product	Starch Content (g·kg^{-1} DM)
Barley	500-516
Oats	400
Milocorn (grain sorghum)	620-741
Corn	630-728
Rye	520
Wheat	580-621
Peas	410
Horse beans	350
Pearl barley product (2% crude fiber)	530
Pearl barley product (7.5% crude fiber)	350
Pearl barley product (10.5% crude fiber)	300
Hominy feed	370
Corn bran	260
Rice bran (<3% husks)	270
Rice bran (3-10% husks)	230
Rice	810
Wheat feed flour	500
Wheat middlings	220
Wheat bran	140
Wheat germ meal	280
Dried potatoes	650
Dried potato pulp	280
Corn gluten feed	190

SOURCE: Borggreve et al., 1975; Murray et al., 2001.

jejunum is the main site of disaccharide digestion. Hore and Messer (1968) found that maltase, sucrase, and lactase activities were present in the small intestine of both cat and dog, although activities found in the dog were only 21, 31, and 37 percent, respectively, of those found in the cat. Specific activity of sucrase in the small intestinal mucosa of milk-fed puppies was 16 $U \cdot g^{-1}$ protein, similar to that of adult dogs fed carbohydrate-free diets (30 $U \cdot g^{-1}$ protein). However, sucrase activity was higher in adult dogs if the diet contained soy (38 $U \cdot g^{-1}$ protein), lactose (59 $U \cdot g^{-1}$ protein), and sucrose (66 $U \cdot g^{-1}$ protein) (Kienzle, 1988). In cats, sucrase activity does not differ between kittens and adult cats (15 vs. 17 $U \cdot g^{-1}$ protein, respectively) even when carbohydrates are included in the diet (Kienzle, 1993d). Maltase activity follows a similar pattern with regard to species and age, but overall activity is higher than that of sucrase (Kienzle, 1988, 1993d). Lactase activity is highest in weanling puppies and kittens, and decreases as the animal matures (Kienzle, 1988, 1993d). This decrease can occur rapidly. Lactase activity was highest in the intestine of young dogs (5 days old) and decreased to levels found in adults by 29 to 61 days of life (Welsh and Walker, 1965).

Kienzle (1993d) reported the presence of two types of lactase in cat intestinal mucosa, one with a pH optimum of 4 or below. It is likely that this form of lactase is a lysosomal enzyme that does not take part in lactose digestion (Kienzle, 1993d). Welsh and Walker (1965) found that the optimal pH for lactase activity in the dog was 5.0, while the optimal pH for sucrase and maltase activities was 6.0.

Kienzle (1993d) found no sucrase or lactase in pancreatic tissue of cats. However, in the intestinal mucosa, average maltase, isomaltase, and sucrase enzyme activities tended to increase from the duodenum to the jejunum and ileum (73 ± 45, 111 ± 58, and 120 ± 58 U of maltase per gram of protein; 31 ± 30, 33 ± 27, and 40 ± 26 U of isomaltase per gram of protein; 12 ± 12, 18 ± 20, and 23 ± 30 U of sucrase per gram of protein, respectively), while maximal activity of lactase occurred in the jejunum (4.9 ± 3.5, 11.4 ± 11.2, and 4.3 ± 3.9 U of lactase per gram of protein). These findings are in agreement with Hietanen (1973) who also found very low maltase and trehalase activities in the small intestinal mucosa of the cat compared to that of the rat, mouse, guinea pig, and rabbit.

α-Amylases are major enzymes involved in degrading the α-1,4-bonds of amylose, amylopectin, and maltodextrins (Colonna et al., 1992). Starch is cleaved in the duodenal cavity by secreted pancreatic α-amylase to disaccharides (maltose), trisaccharides (maltotriose), and branched α-dextrins (Gray, 1992). Amylase activity is higher in dogs than in cats, and dog amylase activity is more sensitive to dietary levels of starch (Kienzle, 1988, 1993a). Glucose, maltose, and higher oligosaccharides are the main soluble products of starch digestion (Sreenath, 1992). Nonresistant starch is completely hydrolyzed in the small intestine and its rate of digestion is influenced by source (van der Meulen et al., 1997).

Although differences due to source exist, ileal and total tract digestibilities of starch in extruded flour (barley, corn, potato, rice, sorghum, and wheat) diets were all greater than 99 percent when fed to ileally cannulated dogs (Murray et al., 1999). The digestibility of raw starch is more variable. Ileal and total tract digestibilities of raw rice or corn starch when fed to ileally cannulated dogs are greater than 90 percent, but ileal digestibilities of raw tapioca and potato starches are only 65 percent and 0 percent, respectively (Schünemann et al., 1989).

Murray et al. (2001) evaluated the ability of small intestinal bacteria of dogs to ferment native and extruded cereal grains, potato starch, and flours using an in vitro model. Average organic matter disappearance was higher for extruded potato starch and cereal grains and for unextruded flours than for their native counterparts, with the exception of wheat flour. These results demonstrated that in vitro microbial fermentation of starches by ileal bacteria can be affected by differences in starch source, fraction, and processed form. These results are supported by Bednar et al. (2001) who also showed a relationship between processing, which reduced total dietary fiber and resistant starch concentrations, and increased starch digestibility.

The extent to which carbohydrates are digested by the cat is controversial. Numerous researchers have reported that the cat has a limited capacity to digest higher molecular weight carbohydrates (Hore and Messer, 1968; Kienzle, 1993a,b,c,d), but Morris et al. (1977) measured high apparent digestibilities by cats of dextrin (97.6 percent) and starch (94.2 percent). These values are quite similar to apparent (total tract) starch digestibility values obtained with extruded grains fed to dogs (Murray et al., 1999). The highest intestinal mucosal amylase activity in cats (26.4 ± 29.4 $U \cdot g^{-1}$ protein) is in the jejunum; amylase activity decreases in the ileum (16.2 ± 14.0 $U \cdot g^{-1}$ protein) and colon (13.0 ± 12.2 $U \cdot g^{-1}$ protein), and is lowest (8.7 ± 6.8 $U \cdot g^{-1}$ protein) in the duodenum (Kienzle, 1993a).

Factors Affecting Digestibility, Absorption, and Utilization

Kienzle (1988) found the activity of the disaccharidases maltase, isomaltase, and sucrase in intestinal mucosa of puppies to be similar to that of adult dogs on carbohydrate-free diets. Maltase activity in the small intestine was 164 ± 40, 407 ± 95, and 162 ± 8 $U \cdot g^{-1}$ protein in 4-week-old milk-fed puppies, 8- to 16-week-old puppies fed a carbohydrate-rich diet, and 12- to 14-week-old puppies fed a low-carbohydrate food, respectively. For the same diets and puppy ages as above, small intestinal isomaltase activity was 50 ± 24, 159 ± 77, and 32 ± 2 $U \cdot g^{-1}$ protein while sucrase activity was 16 ± 9, 61 ± 20, and 13 ± 1 $U \cdot g^{-1}$ protein, respectively.

Similarly, Kienzle (1988) found that enzyme activities in adult dogs increased in the following order: sucrase > isomaltase > maltase. Jejunal enzyme activities were high in

dogs fed sucrose-containing diets—maltase, 363 ± 23; isomaltase, 119 ± 11; and sucrase, 66 ± 8 $U \cdot g^{-1}$ protein, and were low in dogs fed a carbohydrate-free diet—maltase, 226 ± 120; isomaltase, 80 ± 35; and sucrase, 30 ± 13 $U \cdot g^{-1}$ protein, respectively.

Enzymatic hydrolysis of starch in the small intestine depends on the starch fraction, the quantity in the food, interactions with other food components, and transit time from mouth to terminal ileum (Englyst et al., 1992a). Extrusion cooking (the major method of petfood manufacture) promotes depolymerization, decreases molecular weight, and improves hydrolyzability of starch by digestive enzymes (Colonna et al., 1992).

Processing improves the digestibility of starch in cat foods. Grinding increased digestion of wheat starch (from 92 to 97 percent) and corn starch (from 79 to 94 percent) by cats (Morris et al., 1977). Cooking improved corn starch digestibility by cats from 79 to 88 percent (Morris et al., 1977). Cooked corn starch had an apparent prececal digestibility (72.3 ± 16.7 percent; $n = 3$) higher than that of raw corn starch (46.4 ± 36.3 percent; $n = 4$), which demonstrates the beneficial effects of cooking on utilization of starch by the cat (Kienzle, 1993b). Murray et al. (2001) found that high-temperature extrusion of cereal grains (corn, potato, rice, and sorghum) with high total starch content (>80 percent) increased the percentage of rapidly digestible starch and decreased the amount of resistant starch.

Starch digestibility is affected not only by processing but also by plant species. Raw potato and corn starch are poorly digested (19 and 47 percent, respectively) compared to cooked potato starch and corn starch (84 and 84 percent, respectively) (Hilton, 1990). Kienzle (1993b) also found that raw potato starch had a very low apparent prececal digestibility (0.5 ± 38.5 percent; $n = 4$) thought to be due to the structure of potato starch granules, which do not allow easy access of amylase to the substrate.

In plants, starch is stored in crystalline intracellular bodies or starch granules (Englyst et al., 1992a). The shape and crystalline structure of these granules can be one of three types depending on the density and orientation of amylopectin helices of the starch molecules: A (densely packed in an orthogonal pattern), B (less densely pack in a hexagonal pattern), or C (containing both patterns). Cereal starch granules are predominantly A type and are easily degraded by α-amylase and hydrolyzed in the gastrointestinal tract. B-type starches of tubers (potato) and C-type legume starches are more resistant to enzymatic hydrolysis (Englyst et al., 1992a).

Susceptibility of starch granules to α-amylase hydrolysis depends on starch source and starch macromolecular alterations during food processing (Theander and Westerlund, 1987). Activity inhibitors (proteins and glycoproteins) that reduce the action of amylase (Wilcox and Whitaker, 1984) influence starch digestion. Using pigs, Van der Meulen (1997) found higher (1,759 mmol over a 12-hour period) net portal glucose flux for corn starch than for pea starch (1,265 $mmol \cdot 12\ h^{-1}$) and concluded that corn starch was digested faster than pea starch.

The surface area-to-volume ratio of starch in the solid phase increases during milling and grinding, which removes parietal (from cotyledons) polysaccharides (Wuersch et al., 1986) and improves the accessibility of enzymes to starch granules. Therefore, processes that disrupt cereal and legume grains increase the proportion of starch that is digestible. Also, heating (>50°C) starch in an excess of water and at lower moisture conditions with higher temperatures (100 to 150°C) irreversibly gelatinizes the granular structure of starch and improves its solubilization (Colonna et al., 1989). Gelatinized starch molecules recrystallize, or retrograde, upon cooling, and retrograded amylose is poorly digested (Berry, 1986). Factors such as degree of retrogradation, granular structure, and inaccessibility of starch in food can limit ileal starch digestibility to less than 100 percent (Annison and Topping, 1994).

Kienzle (1988) found amylase activity in pancreatic tissue of puppies to be lower (7.1 ± 4.3; 251.5 ± 108.2; 2,098.0 ± 1073; 1,623.0 ± 1431 $U \cdot g^{-1}$ wet weight at 4, 8, 12 and 16 weeks of age, and 8-10 months of age, respectively) than for dogs more than 2 years old (4,665.0 ± 781 $U \cdot g^{-1}$ wet weight). This indicates an age-related ability of the dog to digest starch. In addition, Kienzle (1988) showed that amylase activity in duodenal chyme of adult dogs depends on diet type (Table 4-3).

Since starch digestibility coefficients for cooked or raw rice, oats, and corn in dog diets were higher than 90 percent, Kendall and Holme (1982) concluded that dogs digest cereals and low-fiber cereal by-products efficiently. Washabau et al. (1986) reported that dogs digested rice flour starch optimally, whereas malabsorption of wheat and corn flour occurred. Undigested starch and RS enter the colon and are fermented by hindgut bacteria (Dreher et al., 1984; Washabau et al., 1986).

Kienzle (1993a) measured an average amylase activity of 74.6 ± 42.4 $U \cdot g^{-1}$ wet weight in pancreatic tissue of 25 adult cats fed diets with different starch sources (29 to 37 percent starch, DM basis, from raw corn starch, raw potato starch, or cooked corn starch), and carbohydrate-free diets (two high-fat diets and a high-protein diet). She found that the amylase activity in chyme from the small intestine of adult cats depended on diet type and adaptation period. Values ranged from 11.5 ± 5.5 $U \cdot g^{-1}$ (wet weight) for raw potato starch diets to 53.4 ± 47.3 $U \cdot g^{-1}$ (wet weight) for the cooked corn starch diet.

Meyer and Kienzle (1991) found that cats developed diarrhea after intake of 7 g $sucrose \cdot kg^{-1}$ of body weight (BW) per day, which is in line with the low intestinal activity of sucrase (17 ± 23 $U \cdot g^{-1}$ protein) in cat intestinal mucosa, suggesting a limited capacity to digest this disaccharide. Legrand-Defretin (1994) concluded that the cat is unable to cope with high concentrations of dietary carbohydrate. It

TABLE 4-3 Influence of Diet Type on Amylase Activity ($U \cdot g^{-1}$ wet weight) in Chyme of Adult Dogs

	Treatment				
Intestinal Segment	MM + Su or MM + La ($n = 4$)	SBM + TaS ($n = 4$)	SBM or SBM + Fat ($n = 4$)	Raw Meat or Raw Lungs ($n = 4$)	Dry Dog Food ($n = 4$)
Duodenum	15.8 ± 13.1	38.1 ± 31.3	93.8 ± 75.9	17.3 ± 12.1	146.8 ± 4.2
Jejunum	52.6 ± 38.4	70.9 ± 27.1	178.8 ± 70.0	96.0 ± 36.5	671.9 ± 2.8
Ileum	97.0 ± 26.4	39.7 ± 13.3	43.1 ± 20.2	340.4 ± 278.4	613.5 ± 50.4
Cranial large bowel	70.9 ± 34.4	28.6 ± 27.8	31.0 ± 10.0	152.4 ± 14.4	514.0 ± 60.8
Caudal large bowel	46.6 ± 35.3	30.6 ± 25.0	31.3 ± 20.9	129.3 ± 195.5	332.0 ± 23.3

NOTE: MM + Su = meat meal with sucrose; MM + La = meat meal with lactose; SBM + TaS = soybean meal with tapioca starch; SBM + Fat = soybean meal with fat.
Source: Kienzle, 1988.

also may have no fructokinase (Kienzle, 1994) and may be in a constant state of gluconeogenesis (Legrand-Defretin, 1994).

Morris et al. (1977) found that intestinal β-galactosidase activity decreased with age in kittens (71 to 109 days) but was not affected by addition of sucrose and lactose to an all-meat diet. Kienzle (1993d) also found an age-dependent small intestinal mucosal activity for maltase, which varied from 66 ± 77 $U \cdot g^{-1}$ protein in kittens less than 1 week of age to 102 ± 58 $U \cdot g^{-1}$ protein in adult cats, and an inverse relationship of lactase activity to age varying from 96 ± 66 $U \cdot g^{-1}$ protein in kittens less than 1 week of age to 7 $U \cdot g^{-1}$ protein in adult cats (Table 4-4).

Nutritive Value

The nutritive value of starch depends on degradation of the starch macromolecules, amylose and amylopectin, to glucose, which is absorbed and metabolized to provide energy (Colonna et al., 1992). Therefore, factors that influence starch digestion also affect its nutritive value. Starch has a heat of combustion of 4.18 $kcal \cdot g^{-1}$ (17.5 $kJ \cdot g^{-1}$), and 1 g starch yields 1.11 g glucose (Jequier, 1994). While the heat of combustion for different starches may be similar, starch classification into digestible versus resistant starch suggests different metabolizable energy (ME) values for different starch fractions. Although the net energy value of starch has not been determined in companion animal diets, Borggreve et al. (1975) reported the net energy content of starch in growing pig feed to be 0.34 $kcal \cdot g^{-1}$ (1.42 $kJ \cdot g^{-1}$).

Physicochemical Effects

Osmotic Effects

Unabsorbed disaccharides induce fluid secretion into the small intestinal lumen via osmosis. This, in combination with the rapid colonic fermentation of unabsorbed sugars, results in reduced transit time (Washabau et al., 1986). Kienzle (1993c) reported that disaccharides altered fecal pH and increased fecal water content in cats. Similar results were reported for dogs that consumed diets rich in lactose (Meyer et al., 1989).

Viscosity Properties

Starch granules are not water soluble but hydrate easily in aqueous suspension, swelling about 10 percent in volume. When an aqueous suspension of granules is heated, additional swelling occurs (gelatinization) and a viscous suspen-

TABLE 4-4 Average Activity of Disaccharidases ($U \cdot g^{-1}$ protein) in Small Intestinal Mucosa of Cats in Relation to Age

Age (weeks)	Maltase	Isomaltase	Sucrase	Lactase	n
<1	66 ± 77	30 ± 20	15 ± 8	96 ± 66[a]	10
3-5	108 ± 45	28 ± 17	26 ± 15	69 ± 63[a]	13
6-12	105 ± 53	23 ± 15	12 ± 4	13 ± 9[b]	9
Adult	102 ± 58	35 ± 28	17 ± 23	7 ± 8[b]	78[c]

[a,b]Different superscripts within a column indicate statistical differences ($P < 0.05$).
[c]26 cats, three different parts of the small intestine (duodenum, jejunum, ileum), all diets.
SOURCE: Kienzle 1993d.

sion is produced. The suspension forms a gel upon cooling (Lineback, 1999).

Physiological Effects

Effects on Food Intake, Transit Time, and Fecal Excretion

Houpt et al. (1979) reported that both female and male dogs preferred diets containing sucrose (1 to 20 percent dietary concentration) to a diet containing no sucrose. In addition, female dogs had a greater ($P < 0.05$) preference for 1 percent sucrose-containing diets than did males. No differences between sexes were observed at higher concentrations. These results are supported by Ferrell (1984) who found that puppies (2 to 4 months of age) accepted lactose-, fructose-, and sucrose-containing diets well.

In experiments with pregnant beagle bitches, Romsos et al. (1981) fed two diets, one containing 44 percent metabolizable energy from carbohydrate (corn starch) and the other containing 0 percent metabolizable energy from carbohydrate (the primary energy source was fat). These researchers found that although the gross energy content of the low-carbohydrate diet was similar to that of the high-carbohydrate diet, bitches fed the low-carbohydrate diet consumed slightly less energy (154 kcal ME·kg $BW^{-0.75}$) than dogs fed the high-carbohydrate diet (171 kcal ME·kg $BW^{-0.75}$).

Effects on Availability of Other Nutrients

Disaccharides or starch not completely digested by endogenous enzymes may affect the apparent digestibility of other nutrients in both dogs and cats (Muehlum, 1987). As early as 1914, Ristert reported enhanced calcium absorption due to inclusion of lactose in cat diets. Beynen et al. (2001) also reported an increase in apparent calcium and magnesium absorption by healthy dogs fed diets containing lactulose. However, Kienzle (1994) found no difference in the apparent digestibility of calcium by cats fed diets containing starch (37 percent raw potato starch, 35 percent raw corn starch, or 29 percent cooked corn starch), 36 percent sucrose, or 28 percent lactose compared to cats fed a carbohydrate-free (high-fat) diet. Cats fed the diet containing 36 percent sucrose had a higher apparent digestibility of magnesium (52.6 ± 21.2 percent) and phosphorus (61.2 ± 23.2 percent) compared to cats fed the carbohydrate-free diet (17.8 ± 7.1 and 23.1 ± 9.2 percent, respectively). In this same study, cats fed the raw corn starch diet had a lower apparent protein digestibility (77.1 ± 3.2 percent) compared to cats fed the carbohydrate-free diet (86.9 ± 1.9 percent).

Schultz and Grande (1968) observed no effects of either starch or sucrose supplementation of a low-fat commercial dog food on serum total cholesterol, phospholipids, or triglycerides. The authors suggested that the lack of dietary response may have been related to the low-fat, low-cholesterol dog food used.

Effects on Growth Performance

Inclusion of starch in companion animal diets can impact growth performance. No differences were detected in body weight gain (40.3 vs. 43.1 $g \cdot d^{-1}$, respectively) of growing male dogs fed diets containing either rice (779 $g \cdot kg^{-1}$) or cassava (700 $g \cdot kg^{-1}$) (Kamalu, 1991), although consumption of a 58 percent corn starch diet by 2-month-old female beagles for 8 months resulted in a significant reduction in weight gain compared to beagles fed a carbohydrate-free (26 percent lard) diet (Romsos et al., 1976).

Effects on Reproductive Performance

Although lactose is the predominant sugar in bitch milk, it provides a relatively small amount of the energy in milk. Only 15 percent of the energy in milk from bitches fed a high-carbohydrate diet and 9 percent of the energy in milk from bitches fed a carbohydrate-free diet is accounted for by lactose (Romsos et al., 1981).

Queen's milk has a lactose content of about 3 to 4 percent (Adkins et al., 1997; Dobenecker et al., 1998). Keen et al. (1982) found that the carbohydrate concentration in queen's milk remained constant at approximately 4 percent throughout a 43-day lactation period. Adkins et al. (1997) found a difference in lactose content of colostrum (29.9 $g \cdot L^{-1}$) vs. mature milk (39 to 42 $g \cdot L^{-1}$). Similar results were reported by Kienzle et al. (1985).

Kittens utilize lactose, but the ability to degrade lactose declines after weaning. Newborn kittens have high lactase activity values (96 $U \cdot g^{-1}$ protein) that enable them to digest lactose efficiently (Kienzle, 1993d). There are no data on the effects of disaccharides on the reproductive performance of cats during gestation and lactation.

Romsos et al. (1981) fed pregnant beagle bitches diets containing either 0 percent or 44 percent of metabolizable energy from carbohydrate, 30 percent or 74 percent of metabolizable energy from fat, and a constant 26 percent of metabolizable energy from protein. They found that plasma glucose concentrations were similar between groups except during the week before whelping, when blood glucose concentrations in bitches fed the carbohydrate-free diets were as low as 15 to 20 $mg \cdot dL^{-1}$. None of the bitches on the carbohydrate-containing diet had a significant depression in blood glucose concentration. Blood lactate concentration was 40 percent lower in bitches on a carbohydrate-free diet than in those on a high-carbohydrate diet, although this difference between treatments was not statistically significant.

Romsos et al. (1981) found that fewer puppies from bitches on a carbohydrate-free diet were alive at birth (63 percent) compared to litters from bitches fed the carbohydrate-containing diet (96 percent). Thirty-five percent of the total puppies whelped by bitches on a carbohydrate-free diet were alive at 3 days of age, compared to 93 percent of puppies from bitches on the carbohydrate-containing diet. Rom-

sos et al. (1981) concluded that pregnant bitches require dietary carbohydrates for optimal reproductive performance and survivability of pups. In addition, although the protein intake (10-12 g protein·kg $BW^{-0.75}$) of pregnant bitches in this experiment exceeded that recommended (5.7 g protein·kg $BW^{-0.75}$), the authors concluded that even higher protein intake may have benefited bitches fed the low-carbohydrate diet by providing additional glycogenic precursors.

Additional data from Romsos et al. (1981) indicate the requirement for glucose by pregnant bitches. Bitches fed a carbohydrate-free diet (Romsos et al., 1981) exhibited ketosis, which is associated with hypoglycemia (Felig and Lynch, 1970). This occurred in spite of the fact that dogs are relatively resistant to the development of ketosis (Romsos et al., 1981). Glucose turnover was 20 to 30 percent lower in bitches fed the carbohydrate-free diet compared to those on a carbohydrate-containing diet (Romsos et al., 1981). In addition, Romsos et al. (1981) found depressed (20 percent) body mass of glucose in pregnant bitches fed the carbohydrate-free compared to those on the carbohydrate-containing diet.

Effects on Weight Control and Nutrition of the Obese Animal

Romsos et al. (1976) fed diets with 0 to 62 percent of energy from carbohydrate (corn starch) and a constant amount of energy from protein (approximately 23 percent) (isolated soybean protein; lean beef) to female beagle dogs for 8 months. Dogs fed the high-carbohydrate (62 percent of energy) diet contained less body fat (21.0 ± 2.1 percent) than dogs on the carbohydrate-free diet (27.1 ± 1.8 percent). In contrast, Romsos et al. (1978) found that dogs fed a high-fat diet (51, 20, and 29 percent of energy from fat, protein, and carbohydrate, respectively) had increased body weights compared to dogs fed a high-carbohydrate diet (23, 18, and 59 percent of energy from fat, protein, and carbohydrate, respectively), although energy intake by the two groups of dogs was not significantly different. These results may have implications for obesity management.

Effects on the Geriatric Animal

Dogs and cats become increasingly less able to regulate their blood sugar concentrations as they age (Sheffy et al., 1985; Mosier, 1989), and this disrupted carbohydrate metabolism at times leads to diabetes. Advanced age generally does not reduce the apparent digestion coefficients of carbohydrates by dogs. Zimmer (1983) concluded that there was no advantage to feeding a diet with reduced fiber to the older dog.

Health-Related Characteristics

Gastrointestinal Tract Health

Incomplete digestion of some disaccharides, as in the case of lactose intolerance, results in malabsorption of simple carbohydrates and may cause diarrhea, abdominal pain, and cramps. Holtug et al. (1992) ascribed these symptoms in humans to the accumulation of carbohydrates in the hindgut in too great a quantity for microbial fermentation, resulting in osmotic diarrhea. Zentek (1995) found that in vitro incubation of dog ileal chyme with glucose or galactose resulted in a reduction of pH to 5.18 and 5.15, respectively. In comparison, incubation with lactose or starch (corn starch or potato starch) resulted in less severe reductions in pH (5.85, 6.48, and 7.13, respectively).

Glycemic Response

The rate and extent to which starch is digested and absorbed, and the resulting glucose and insulin responses, vary considerably depending on starch source and degree of food processing (Englyst et al., 1999). Large variations in postprandial glucose concentrations and insulin secretory responses to ingestion of different foods have been observed in dogs (Nguyen et al., 1994). For example, Bennett and Coon (1966) reported that adult dogs fed diets containing 59 percent carbohydrate as lactose exhibited a flattened blood glucose curve compared to dogs fed a glucose-containing diet. They surmised that lactose was poorly absorbed by dogs. It is possible that foods resulting in a lower glycemic response would be beneficial for diabetic or obese dogs. Nguyen et al. (1998) concluded that the amount of starch consumed is the major determinant of the glycemic response of adult healthy dogs. Once among-subject variation is accounted for, 70 percent of the remaining variance in glycemic response is explained by differences in rapidly available glucose content of test meals (Englyst et al., 1999).

Postprandial hyperglycemia and insulin secretion depend on the ratio of amylose to amylopectin consumed (Nguyen et al., 1998). Nguyen et al. (1998) found a positive linear correlation between the starch content of foods and postprandial plasma glucose and insulin response curves, demonstrating that the amount of starch consumed from different complete diets also is a major determinant of the glycemic response of healthy adult dogs.

Sunvold and Bouchard (1998) fed adult dogs dry, extruded diets formulated to contain 30 percent starch from either corn, wheat, barley, rice, or sorghum. Dogs consuming the rice diet exhibited the highest ($P < 0.05$) average blood glucose values and greatest ($P < 0.05$) area-under-the-curve postprandial glucose values, as well as the highest ($P < 0.05$) blood insulin values and the greatest ($P < 0.05$) area-under-the-curve insulin values. Diets containing sorghum resulted in the lowest blood glucose and area-under-the-curve glucose values ($P < 0.05$), while diets containing barley resulted in the lowest blood insulin and area-under-the-curve insulin values ($P < 0.05$). Diets containing corn or wheat resulted in intermediate blood glucose and insulin values, as well as intermediate glucose and area-under-the-curve insulin values. These data indicate that the source of

starch influences the postprandial glucose and insulin responses in adult dogs.

FERMENTABLE CARBOHYDRATES (LACTOSE, CERTAIN OLIGOSACCHARIDES, DIETARY FIBERS [DF], AND RESISTANT STARCH [RS])

Presence in Foodstuffs

Fermentable carbohydrates include certain oligosaccharides, fermentable fibers, RS, and under certain conditions, lactose. These carbohydrates resist hydrolytic digestion in the small intestine but are fermented by microbes indigenous to the lower gastrointestinal tract of dogs and cats.

The major sources of fermentable carbohydrates in dog and cat foods are cereals, legumes, and other plant ingredients. Table 13-1 presents NSP concentrations of cereal grains and legumes and plant by-products used in dog and cat foods. Oligosaccharides can be produced synthetically (Crittenden and Playne, 1996) in addition to being found in nature. Wheat, barley, and other dietary ingredients of plant origin are important sources of fructooligosaccharides and inulin (Monsan and Paul, 1995; Campbell et al., 1997). Soybean is a major source of raffinose, stachyose, and verbascose. Table 4-5 lists the nondigestible oligosaccharides that may be found in dog and cat foods.

Hemicelluloses are a type of DF well fermented by nonruminants (Keys and DeBarthe, 1974; Stanogias and Pearce, 1985). Hemicelluloses (quantified as arabinoxylans) are commonly found in wheat and rye (4 to 8 percent), while β-glucans are more prominent in oats and barley (2 to 9 percent; Prosky and DeVries, 1992; Cho et al., 1997). Pectin-rich foods include apple pomace, citrus peel, and sugarbeet pulp (Prosky and DeVries, 1992).

TABLE 4-5 Molecular Structure and Chemical Linkages of Oligosaccharides with Bifidogenic Effects in Dog and Cat Foods[a]

Name	Molecular Structure[b]	Linkages Between Monomers
Lactosucrose	Ga-Gu-Fr	β
Raffinose	Ga-Gu-Fr	α-1,6
Galactooligosaccharides	$(Ga)_n$-Gu	β-1,4, β-1,6
Fructooligosaccharides	$(Fr)_n$-Gu	β-1,2
Soybean oligosaccharides	$(Ga)_n$-Gu-Fr	α-1,6
Isomaltooligosaccharides	$(Gu)_n$	α-1,6
Xylooligosaccharides	$(Xy)_n$	β-1,4
Palatinoseoligosaccharides	$(Gu\text{-}Fr)_n$	α-1,6
Glycosylsucrose	$(Gu)_n$-Fr	α-1,4
Maltooligosaccharides	$(Gu)_n$	α-1,4
Cyclodextrins	$(Gu)_n$	α-1,4 cyclic structure
Gentiooligosaccharides	$(Gu)_n$	β-1,6

NOTE: Fr = fructose; Ga = galactose; Gu = glucose; Xy = xylose.
[a]Sako et al., 1999.

Resistant starch is a variable component of virtually all starchy food ingredients and is higher in foods of larger particle size, in undercooked ingredients, in cooked and cooled foods, and in chemically modified starches (Brown et al., 2001). Common sources of RS include high-amylose corn starch, raw potato starch, most legumes, and commercially available, chemically modified starches.

In addition to dietary fiber naturally present in food ingredients, pure fiber sources can be added to petfoods. Carrageenann and other gums (added at <5 percent of diet dry matter) are used as gelling agents in canned dog and cat foods (Brown, 1989) and, therefore, are a source of fermentable carbohydrates.

Digestion, Absorption, and Utilization

Dietary fibers, RS, and most oligosaccharides resist hydrolysis by endogenous enzymes. They pass through the small intestine undigested and are fermented by microbes in the colon to gases (carbon dioxide, hydrogen, methane) that are excreted and short-chain fatty acids (SCFAs) (mainly acetate, propionate, butyrate) and lactate (Roediger, 1980; Roberfroid, 1993) are produced. Short-chain fatty acids are absorbed through the intestinal wall primarily via passive diffusion (Argenzio, 1989; Fleming et al., 1991). Herschel et al. (1981) determined that SCFAs and Na^+ were absorbed rapidly, and at the same rate, in the colonic mucosa of dogs, and reported SCFAs to be the major anions accountable for osmotic absorption of water from the colon.

Portal concentrations of SCFAs exceed arterial concentrations, indicating that most SCFAs are cleared by the liver (Rerat et al., 1987). However, some acetate is found in the systemic blood circulation (Buckley and Williamson, 1997) and can be oxidized by muscle tissue for energy (Pouteau et al., 1998a,b; Remesy et al., 1992). Propionate is taken up by the liver from the portal blood and is converted to succinyl coenzyme A. Butyrate, on the other hand, is oxidized by the intestinal mucosa and serves as the preferred energy substrate of colonocytes (Roediger, 1980; Firmansyah et al., 1989; Drackley and Beaulieu, 1998). Lactate is a precursor for gluconeogenesis (Delzenne and Roberfroid, 1994).

The carnivorous nature of cats, their relatively small colon (<20 percent of the total gastrointestinal tract length), and their lack of a functional cecum suggest that they may not utilize DF as extensively as do other nonruminants (Kienzle, 1993d; Maskell and Johnson, 1993). However, Kienzle (1993b) noted reduced pH values of large bowel digesta and feces after cats ingested raw corn starch. This effect was ameliorated by the administration of oral antibiotics. This undoubtedly is a result of SCFAs from increased microbial hindgut fermentation of starch.

Sunvold et al. (1995b) fed domestic, short-hair cats diets containing 0 or 9.5 percent supplemental TDF from either beet pulp (a moderately fermentable fiber), cellulose (a relatively unfermentable fiber), a 3:1 cellulose:gum arabic

mixture, or two different blends of fibers (35 percent citrus pectin + 30 percent locust bean gum + 20 percent carob bean gum + 15 percent guar gum or 60 percent beet pulp + 22 percent rice bran + 10 percent citrus pectin + 8 percent carob bean gum). While cats consuming the 0 percent supplemental fiber diet (control; 1.7 percent TDF) had the highest ($P < 0.05$) apparent dry matter and organic matter digestibility values, TDF digestibility was increased ($P < 0.05$) by consumption of beet pulp (38.2 percent) or the two fiber blends (50.6 and 41.1 percent, respectively) compared to the control diet (5.3 percent). Total dietary fiber digestibilities of cellulose (8.9 percent) and the 3:1 cellulose:gum arabic mixture (5.7 percent) were similar to the control diet.

Sunvold et al. (1995b,c) showed that using either dog or cat fecal inoculum, guar gum, and citrus pectin were highly fermentable in vitro in comparison to pure cellulose, while oat fiber, xanthan gum, gum talha, gum karaya, gum arabic, carob bean gum, locust bean gum, rice bran, and beet pulp were intermediate. Furthermore, incubation with fecal inoculum from cats resulted in a greater ($P < 0.05$) quantity of SCFAs and a higher ($P < 0.05$) proportion of acetate from in vitro fermentation with either cellulose, beet pulp, citrus pulp, or citrus pectin when compared to fecal inoculum from dogs, pigs, cattle, horses, or humans (Sunvold et al., 1995d). These data refute the assumption that cats are incapable of significant fiber fermentability.

Dogs are capable of utilizing plant sources of fermentable carbohydrates. Lignocellulose, hemicelluloses, and cellulose were reported to have digestibility values of approximately 33, 47, and 18 percent, respectively (Visek and Robertson, 1973). Kendall and Holme (1982) evaluated the digestibility of 21 plant materials by dogs. They reported that ground wheat, barley meal, flaked corn, oat meal, and wheat germ meal were well digested (72 to 96 percent apparent energy digestibility coefficients). Wheat feed, distiller's by-products, walnut meal, almond meal, dried molasses sugar beet pulp, and locust bean meal were less digestible, probably because of their higher fiber content (39 to 59 percent apparent energy digestibility coefficients).

Swanson et al. (2001) investigated alternative fiber sources using an in vitro fermentation technique to evaluate their usefulness for incorporation in companion animal diets. On a dry matter (DM) basis, substrates contained between 55 and 86 percent TDF and had varying ratios of insoluble to soluble fiber. Accordingly, fermentation characteristics also varied greatly. Apple pomace, carrot pomace, and flaxseed had the greatest fermentability, while grape pomace, pistachio, and a blend of fruits (peach, almond, nectarine, and plum) were poorly fermented. Pea hulls and tomato pomace had an intermediate level of fermentability.

Silvio et al. (2000) fed dogs diets containing 10 percent DF from cellulose (100 percent), pectin (100 percent), or a mixture of the two (66 percent cellulose + 33 percent pectin or 66 percent pectin + 33 percent cellulose). They reported that total tract digestibility by dogs increased linearly for dry matter (from 81.3 to 88.3 percent), ADF (from 48.8 to 94.1 percent), and TDF (from 37.7 to 69.0 percent) with increases in dietary pectin concentration. They attributed the increased digestibility to the extensive fermentation of pectin compared to the slow fermentation of cellulose.

Lactose is a unique disaccharide in that it is not rapidly digested by adult animals. Its digestibility depends on the animal's individual enzymatic capacity (Muehlum et al., 1989). Unabsorbed lactose is readily fermented by colonic microflora (Cummings et al., 1997; Rerat, 1978). When Bennett and Coon (1966) fed adult dogs diets containing 59 percent carbohydrate from either sucrose or lactose, they observed diarrhea and a flattened blood glucose curve after feeding the lactose-containing diet. They surmised that lactose was poorly digested by dogs.

Factors Affecting Digestibility, Absorption, and Utilization

The molecular structures and linkages between monomeric subunits influence the resistance of fermentable carbohydrates to hydrolytic digestion (Roberfroid, 1993). Furthermore, the presence of small intestinal bacteria suggests that certain nondigestible carbohydrates may be fermented anterior to the colon (Willard et al., 1994; Sparkes et al., 1998a). Such fermentation is likely to be influenced by the type of carbohydrate and quantity consumed.

The source and solubility of fermentable carbohydrates are the most important factors in determining fermentability. Soluble fibers generally are better energy substrates (due to their increased rate and extent of fermentation) for gastrointestinal microorganisms than insoluble fibers. Zentek (1996) compared the effects of cellulose (insoluble fiber source) and pectin and guar (soluble fiber sources) at 10 percent of the diet on apparent nutrient digestibility by dogs. He determined the apparent digestibility of dry matter for the cellulose diet (80.3 ± 2.0 percent) to be lower ($P \leq 0.05$) than for the pectin (89.6 ± 1.7 percent) or guar (88.1 ± 1.3 percent) diets. Similarly, ADF digestibility was lower ($P \leq 0.05$) for the cellulose-containing diet (20.2 ± 11.8 percent) than for diets containing guar (47.1 ± 6.3 percent) or pectin (75.0 ± 5.9 percent). These results are supported by Muir et al. (1996) who fed dogs diets containing varying ratios of pectin (soluble fiber; SF) and cellulose (insoluble fiber) (2.5 percent cellulose and 5 percent pectin [low-cellulose mixture; LCM], 5 percent cellulose and 2.5 percent pectin [high-cellulose mixture; HCM], or 7.5 percent cellulose [CEL]). Increasing dietary cellulose concentrations linearly decreased ($P < 0.05$) TDF digestibility values (LCM, 47.8 percent; HCM, 5.0 percent; SF, –12.5 percent).

Fahey et al. (1990a) reported that dogs fed meat-based diets containing 12.5 percent TDF from primarily insoluble fiber sources (beet pulp, tomato pomace, peanut hulls, wheat bran, and alkaline hydrogen peroxide-treated wheat straw) digested between 29 and 37 percent TDF. In a subsequent study, Fahey and coworkers (1992) determined that dogs fed diets containing 7.5 percent beet pulp had higher ($P < 0.05$)

TDF digestibility values than dogs fed diets containing 7.5 percent oat fiber (61.1 vs. 39.7 percent, respectively).

The concentration of fermentable carbohydrates in the diet also influences their utilization. Fahey et al. (1990b) demonstrated that increasing concentrations of beet pulp (0, 2.5, 5, 7.5, 10, or 12.5 percent) in a meat-based dog diet linearly ($P < 0.05$) decreased dry matter and organic matter digestibility coefficients. Total dietary fiber digestibility exhibited a cubic response ($P < 0.05$), with the 2.5 percent beet pulp diet having the highest TDF digestibility (63 percent) and the 10 percent beet pulp diet having the lowest TDF digestibility (49 percent). Conversely, Allen et al. (1981) found no effect on apparent dry matter or starch digestibilities for adult dogs fed corn-based diets supplemented with distillers dried grains with solubles (DDGS) at 0, 4, 6, or 8 percent of the diet. However, higher concentrations of DDGS (15.7 percent) depressed the apparent digestibility of DM (79.9 percent) compared to 0 or 8.9 percent DDGS (84.8 and 83.6 percent, respectively).

Normal extrusion conditions reduce the average molecular weight of native starches and may facilitate redistribution of the ratio of insoluble to soluble fiber (Camire et al., 1990). Camire et al. (1990) reported that extrusion reduced the molecular weight of amylopectin and attributed this change to the shear force generated by the extruder. Using an in vitro canine model, Bednar et al. (2001) determined that the processing of cereal into flour markedly reduced RS and TDF concentrations, increased solubility of the substrates, and decreased SCFA production (because more disappeared during ileal in vitro digestion, decreasing the quantity of potentially fermentable substrate). Depending on type, RS is moderately to extensively fermented (Murray et al., 1998; Brown et al., 2001). Apparent carbohydrate digestibility was lower ($P < 0.05$) for diets containing RS from high-amylose corn (42.6 percent) compared to a V-complex-type (fat-carbohydrate complex) RS (76.1 percent) (Murray et al., 1998).

Nutritive Value

Non-starch polysaccharides are fermented to SCFAs by hindgut microflora, and these are used as an energy source by dogs (Banta et al., 1979). Von Engelhardt et al. (1989) reported that 95 to 99 percent of SCFAs produced in the hindgut of mammals are absorbed. Stevens et al. (1980) reported that the amount of SCFA absorbed per kilogram body weight varied among species and was 7.5 $mmol \cdot d^{-1}$ in the canine large intestine.

Due to energy losses (gases and heat) during fermentation and production of ATP from oxidation of SCFAs, digestible energy from NSPs is not all used for metabolism by the host animal (Wisker et al., 1997) and is, therefore, less efficiently used than energy from glucose oxidation. Depending on the extent of fermentation, NSPs have an energy value of 0 to 2.4 $kcal \cdot g^{-1}$ (0 to 10.08 $kJ \cdot g^{-1}$) (Schneeman, 1994; Molis et al., 1996). Roberfroid et al. (1993) estimated the caloric value of a fructosyl unit from oligofructose to be between 1 and 1.5 $kcal \cdot g^{-1}$ (4.18 and 6.28 $kJ \cdot g^{-1}$), which is approximately 30 to 40 percent of the value of a digested fructose molecule. The energy value of RS has been estimated at 2 $kcal \cdot g^{-1}$ (8.37 $kJ \cdot g^{-1}$) (Brown et al., 2001). In the absence of any specific literature on the caloric value of fermentable carbohydrates for companion animals, the values listed above are presumed to be applicable to the dog and cat. It is probable that the dog and cat would gain similar amounts of digestible energy from NSPs, since in vitro fermentation of fibrous substrates resulted in similar amounts of SCFA production when either dog or cat fecal inoculum was used (Sunvold et al., 1995a).

There are no data on digestible energy or energy values from NSP fermentation specifically related to dog or cat microflora. Significant differences among species in the efficiency of NSP energy utilization (Wisker et al., 1997) make it important to generate data on net energy values of NSP for dog and cat foods. Herschel et al. (1981) concluded that although the total energetic contribution of SCFAs absorbed in the dog colon (approximately 7 percent) may be relatively small, their absorption is significant to normal colonic absorptive processes.

The digestible energy of 21 plant materials used in dog diets was estimated to range from 72 to 96 percent for whole ground wheat, barley meal, flaked maize, refined flour, vital gluten, feeding oat meal, and wheat germ meal (Kendall and Holme, 1982). However, low apparent digestible energy values of 34 to 62 percent were measured for other plant-based feed ingredients (wheat feed, walnut meal, almond meal, dried molasses sugar beet pulp, locust bean meal, and two distillers by-products). The wide variation in digestible energy content of these plant materials can be attributed to the higher fiber content of the less digestible products.

Physicochemical Effects

Osmotic Effects

Because SCFAs are weak anions, they may exert osmotic pressure in the colon and increase fecal water content (Schneeman, 1987; Roberfroid, 1993). However, the rapid and extensive absorption of SCFAs (Herschel et al., 1981; Von Engelhardt et al., 1989) likely compensates for any net osmotic action. In fact, SCFAs are thought to be responsible for promoting water reabsorption from the colonic lumen in both dogs and humans (Herschel et al., 1981; Bowling et al., 1993). Therefore, the osmotic and reabsorptive properties of SCFAs appear to be dose dependent. At extremely low or high concentrations, SCFAs can be expected to increase fecal water content. However, moderate SCFA concentrations generally decrease fecal water content.

Water-Binding Capacity

Viscous polysaccharides (e.g., pectins, gums) generally possess a high water-holding capacity. Resistant starches have a low capacity for water absorption compared to other fibers. As the water-binding capacity of a fiber increases, it becomes more susceptible to microbial degradation (Schneeman, 1987).

Bourquin et al. (1993) reported that the water-holding capacity of in vitro-fermented fiber residues was greatest for carboxymethylcellulose and gum arabic and lowest for oat and soy fibers. Similarly, the disappearance of organic matter was greatest for gum arabic and lowest for oat fiber. Although carboxymethylcellulose had a high water-holding capacity, it was not extensively fermented by human fecal bacteria. McBurney (1991) measured the in vitro water-holding capacity (a predictor of the stool bulking effect of a fiber) of purified fiber sources (psyllium hydrocolloid, yeast cell walls, and mixed fiber (pea fiber, oat fiber, sugar beet fiber). Water-holding capacity of unfermented substrates differed ($P < 0.05$), with psyllium having the greatest capacity.

Using a diet containing 10 percent (as-fed basis) of cellulose, guar gum, and pectin for dogs fed 18 to 21 g DM·kg BW^{-1}·d^{-1}, Zentek (1996) reported that the soluble fibers (pectin, guar gum) had higher hydratability than the less soluble cellulose and suggested that DF exerted effects on intestinal digestive physiology that depended on chemical composition and the amount of DF present.

Viscosity Properties

Certain NSPs thicken when mixed with liquid, creating a viscous solution. Viscous NSPs include gums, pectins, and β-glucans. Oat and barley β-glucans and pectin form gels in aqueous solutions (Meyer and Tungland, 2001; Wood, 2001). Increased viscosity is associated with prolonged gastric emptying, increased intestinal transit time, and slowed nutrient absorption (Schneeman, 1987).

Murray et al. (1999) tested an induced viscosity fiber (IVF; alginate with added calcium and citrate) in an enteral diet fed to ileal-cannulated dogs. Compared to a control enteral formula, dogs fed the IVF diet had similar nutrient digestibilities at the ileum but higher ($P < 0.05$) total tract digestibilities of dry matter, organic matter, and crude protein. Apparent fat digestibility was lower ($P < 0.05$) for dogs consuming the IVF diet, while apparent starch digestibility was similar between the two groups. Mean serum glucose response was lower ($P < 0.05$) for dogs consuming the IVF formula compared to the controls. The authors attributed these differences to a probable increase in viscosity of the digesta, thereby reducing starch digestion and/or glucose absorption.

Physiological Effects

Effects on Food Intake, Transit Time, and Fecal Excretion

Table 4-6 summarizes the effects of nondigestible carbohydrates on intestinal transit time and fecal excretion. The diverse physical properties of fermentable carbohydrates, as well as their concentration in the diet, determine their specific physiological effects. These effects embody food intake, intestinal transit time, nutrient absorption, fecal volume, and intestinal microflora (Kritchevsky, 1988; Zentek, 1996). Carbohydrates entering the large bowel (DF, RS, and nondigestible oligosaccharides) exert effects through either their physical presence, their fermentation products (i.e., SCFAs), or modification of the colonic microflora. Inclusion of dietary fiber in dog foods may impact food intake. Proposed causes of depressed intake include decreased palatability of the diet, digestive upset (i.e., flatulence, diarrhea), and mechanical satiation.

In tests with dry dog foods containing either 1.5 percent crude fiber and 387 kcal per 100 g (1,619 kJ per 100 g) or 12.3 percent crude fiber and 278 kcal per 100 g (1,163 kJ

TABLE 4-6 Characteristics of Selected Fibers and Their Effects on Intestinal Transit Time and Fecal Characteristics of Dogs and/or Cats[a]

	Fiber Properties[b]		Animal Effects		
Fiber Type	Fermentability	Viscosity	Wet Fecal Volume	Fecal Moisture	Transit Time
Psyllium	Y	Y	NI	NI	↑
Guar gum	Y	Y	NI	↑	↑
Pectin	Y	Y	NI	↑	↓
Purified cellulose	N	N	↑	↑	↔
Beet pulp	Y	N	↑	↑	↓
Wheat bran	N	N	↑	↑	↔

[a]Abbreviations used: Y = yes; N = no; ↑ = increase; ↓ = decrease; ↔ = no effect; NI = no information available.
[b]The dietary fiber characteristics of fermentability and viscosity were chosen based on the recommendations of the Institute of Medicine (2001) as meaningful alternative labels for the terms soluble and insoluble fiber.

per 100 g) (as-fed basis), dogs consumed less ($P < 0.05$) metabolizable energy from the higher-fiber diet although the weight of food consumed by each group was similar (Jewell and Toll, 1996). These results were supported by Jewell et al. (2000) who determined that dogs fed a diet containing 19.4 percent crude fiber and 235 kcal per 100 g (983 kJ per 100 g) (as-fed basis) consumed a similar quantity of food, but 27 percent fewer calories ($P < 0.05$), than dogs consuming a 1.7 percent crude fiber, 365 kcal per 100 g (1,527 kJ per 100 g) diet (as-fed basis). In a subsequent experiment using dry diets containing either 1.5 percent crude fiber and 365 kcal per 100 g (1,527 kJ per 100 g) or 20.6 percent crude fiber and 235 kcal per 100 g (983 kJ per 100 g) (as-fed basis), Jewell and Toll (1996) again reported that dogs fed the higher-fiber diet voluntarily consumed less metabolizable energy ($P < 0.05$). However, in this study, dogs also consumed a lower quantity ($P < 0.05$) of the diet containing 20.6 percent crude fiber as compared to the low-fiber diet. Supplementation of a low-energy diet with moderate concentrations of insoluble fiber had no effect on satiety when fed to dogs at an energy intake corresponding to allowances for weight reduction, indicating that mechanical satiation is not a mechanism by which insoluble fiber decreases food intake (Butterwick et al., 1994).

Fermentable carbohydrates also affect intestinal transit time. In general, diets with high concentrations of viscous polysaccharides result in more bulk in the digesta, prolonged gastric emptying, and slowed transit through the small intestine of humans and dogs (Eastwood, 1992; Lewis et al., 1994).

Russell and Bass (1985) reported that the time to empty one-half of the stomach contents was longer ($P < 0.05$) in dogs dosed with either 3 percent psyllium or 1.5 percent guar gum solutions compared to dogs consuming 0 to 1.0 percent psyllium or guar gum solutions. The authors concluded that gastric emptying slowed as fiber content and viscosity of the meal increased.

Dogs fed a diet containing 4.8 percent pectin (highly fermentable fiber) exhibited a lower ($P < 0.05$) ingestion-to-excretion time than dogs fed a control (starch) diet (Lewis et al., 1994). Inclusion (4.4 percent) of either corn fiber or coarse or fine cellulose (lowly fermentable fibers) in the diet did not significantly alter gastrointestinal transit time in dogs (Lewis et al., 1994). Fahey et al. (1990b) also reported that increasing the dietary concentrations of beet pulp (a moderately fermentable fiber) was associated with a linear decrease ($P < 0.06$) in mean retention time of digesta.

The most established effect of dietary fiber is its impact on stool weight (Cummings et al., 1992). Fecal dry matter consists primarily of bacterial cells (40 to 55 percent; Cummings and Macfarlane, 1991), with the remainder being composed of unfermented dietary fiber and undigested compounds (Kritchevsky, 1988; Tetens et al., 1996). Fahey et al. (1990a) reported that dogs fed diets containing approximately 12.5 percent TDF from either beet pulp, tomato pomace, peanut hulls, or wheat bran excreted a greater ($P < 0.05$) quantity of wet feces than dogs consuming a fiber-free control diet. Fecal dry matter content was reduced ($P < 0.05$) only for dogs consuming beet pulp.

Zentek (1996) measured increased fecal moisture percentage for dogs consuming pectin (70.5 ± 3.6 percent) or guar gum (74.1 ± 2.9 percent) compared to cellulose (61.1 ± 1.8 percent). The author noted that feces from dogs fed pectin or guar gum were softer than those from dogs fed cellulose and concluded that dogs tolerate soluble complex carbohydrates such as pectin and guar gum only in limited amounts before negative influences on fecal quality occur.

Sunvold et al. (1995b) reported increased ($P < 0.05$) fecal output and fecal moisture for cats fed a diet containing 9.5 percent supplemental fiber from beet pulp (34 g wet feces per day, 75 percent fecal moisture) compared to cats consuming a control diet with no added fiber (12 $g \cdot d^{-1}$, 58 percent). However, a diet with 9.5 percent added fiber from cellulose did not affect wet fecal output (18 $g \cdot d^{-1}$) or fecal moisture (53 percent). Fecal consistency and number of defecations per day were not significantly affected by either of these fibers. In the same study, cats consuming a diet with 9.5 percent added fiber from a blend of rapidly fermentable fibers (35 percent citrus pectin, 30 percent locust bean gum, 20 percent carob bean gum, and 15 percent guar gum) exhibited watery stools, increased wet fecal output, increased fecal moisture content, and increased number of defecations per day ($P < 0.05$). The divergent effects of these three diets can be attributed to the fermentation characteristics of their respective fibers: citrus pectin and gums are rapidly fermentable, beet pulp is moderately fermentable, and cellulose is poorly fermented.

Diez et al. (1998) studied the effects of supplementing dog diets (20.8 percent beef minced meat, 69.2 percent flaked corn, 6.7 percent corn oil, and 3.3 percent vitamin-mineral mix, DM basis) with 7 percent inulin, guar gum, or sugar beet fiber (SBF). Compared to the other dietary fibers, inulin resulted in the numerically lowest ($P > 0.05$) increase in wet fecal volume (65.6, 96.0, 119.1, and 128.4 $g \cdot d^{-1}$ for control, inulin, guar gum, and SBF, respectively), indicating a mild bulking effect. Inulin did not increase dry fecal output but did increase ($P < 0.05$) fecal moisture from 65.6 percent (control) to 73.0 percent. Guar gum supplementation resulted in 76.5 percent fecal moisture (greater [$P < 0.05$] than the control and inulin treatments), while SBF supplementation resulted in 75.3 percent fecal moisture, which was not different from inulin or guar gum treatments.

Effects on Availability of Other Nutrients

Table 4-7 summarizes the effects of nondigestible carbohydrates on nutrient digestibility. Dietary fibers that form gels in the gastrointestinal tract act as a steric hindrance to enzymatic hydrolysis (Colonna et al., 1992). Other mechanisms by which fermentable carbohydrates may impact nu-

TABLE 4-7 Characteristics of Selected Fibers and Their Effects on Nutrient Digestibility by Dogs and/or Cats[a]

			Animal Effects			
			Ileal Nutrient Digestibility		Total Tract Nutrient Digestibility	
	Fiber Properties[b]					
Fiber Type	Fermentability	Viscosity	DM	CP[c]	DM	CP[c]
Pectin	Y	Y	↔	↔	↑	↓
Cellulose	N	N	↔	↔	↓	↑ ↔
GOS[d]	Y	N	↓	↔	↓	↓
Beet pulp	Y	N	NI	NI	↓	↓ ↔
FOS[e]	Y	N	↔	↔	↔	↔
XOS[f]	Y	N	↔	↔	↔	↔
MOS[g]	Y	N	↔	↔	↔	↔

[a]Abbreviations used: Y = yes; N = no; ↑ = increase; ↓ = decrease; ↔ = no effect; NI = no information available.
[b]The dietary fiber characteristics of fermentability and viscosity were chosen based on the recommendations of the Institute of Medicine (2001) as meaningful alternative labels for the terms soluble and insoluble fiber.
[c]Crude protein.
[d]Glucooligosaccharides.
[e]Fructooligosaccharides.
[f]Xylooligosaccharides.
[g]Mannanoligosaccharides.

trient availability include altering transit time and forming complexes between the hydroxyl groups of fibrous compounds and other nutrients (Fernandez and Phillips, 1982; Eastwood, 1992).

Silvio et al. (2000) reported that replacing dietary cellulose with pectin in dog diets containing 10 percent added fiber (DM basis) led to an increase ($P < 0.05$) in total tract dry matter and gross energy digestibility, but a decrease ($P < 0.05$) in crude protein digestibility. However, since ileal crude protein digestibility was unaffected by fiber type, the authors concluded that the decrease in apparent crude protein digestibility likely was due to increased fermentation in the colon, leading to increased microbial nitrogen in the feces. These results are supported by Flickinger et al. (2000) who determined that 6 percent dietary inclusion of two different types of glucooligosaccharides reduced ($P < 0.05$) total tract, but not ileal, crude protein digestibility by adult dogs.

Harmon et al. (1999) demonstrated that addition of 7.5 percent cellulose, beet pulp, or soy fiber to canned dog diets reduced ($P < 0.05$) total tract dry matter digestibility and tended ($P = 0.09$) to reduce crude protein digestibility compared to a diet with no added fiber. Notably, dogs fed the cellulose diet had a greater total tract crude protein digestibility than did dogs consuming either the beet pulp or the soy fiber diets. Ileal digestibilities of dry matter and crude protein were similar for dogs in all groups. The authors noted that fiber fermentability can impact estimates of nutrient digestibility, and increased microbial fermentation inversely affects crude protein digestibility as a result of greater microbial protein excretion in feces.

Incorporation of a blend of fructooligosaccharides (rapidly fermentable) and sugar beet fiber (moderately fermentable) in a 4:1 ratio at 0, 5, or 10 percent (DM basis) into a corn-based diet did not significantly alter the digestibility of dry matter, organic matter, or ether extract by healthy dogs (Diez et al., 1997a). Apparent crude protein digestibility was lower ($P < 0.05$) for dogs consuming the highest concentration of the fiber blend. Similarly, Strickling et al. (2000) reported no significant effects of dietary supplementation (0.5 percent) of fructooligosaccharides, xylooligosaccharides, or mannanoligosaccharides on ileal or total tract digestibility of dry matter or crude protein. However, Zentek et al. (2002) reported decreased digestibility of dry matter, crude protein, and nitrogen-free extract for dogs fed diets supplemented with 5.9 percent mannanoligosaccharides. The difference between the findings of these two studies likely is due to the level of supplementation employed (0.5 vs. 5.9 percent).

Zuo et al. (1996) investigated the effects of galactooligosaccharides (raffinose, stachyose, and verbascose) on nutrient digestion by dogs. Low-oligosaccharide soybean meal did not improve nutrient digestibility. Furthermore, total tract digestion of all oligosaccharides was >100 percent, leading the authors to conclude that low-oligosaccharide soybean meal is digested similarly to conventional soybean meal. These data are supported by Muehlum et al. (1989) who reported total tract digestibility values of 97 to 99 percent for dogs. Furthermore, Zentek et al. (2002) reported no reduction in nutrient digestibility for dogs fed 5.9 percent dietary transgalactooligosaccharides.

Sunvold et al. (1995b) found that supplementing cat diets with 9.5 percent TDF from either beet pulp or cellulose reduced ($P < 0.05$) the apparent digestibility of dry matter and organic matter compared to diets with no added fiber. Contrary to the dog studies presented above, neither fiber type

significantly affected total tract crude protein digestibility. However, when a combination of citrus pectin, locust bean gum, carob bean gum, and guar gum (9.5 percent added fiber) was fed, dry matter, organic matter, crude protein, and lipid digestibilities were depressed markedly ($P < 0.05$). Sunvold et al. (1995b) attributed this to the rapid fermentability of the fiber combination, possibly causing small intestinal bacterial overgrowth or resulting in increased luminal viscosity and interference with the action of pancreatic enzymes and bile acids.

Fernandez and Phillips (1982) found that when the upper small intestine of healthy dogs was perfused with a solution containing iron (ferrous sulfate) and psyllium, they exhibited reduced ($P < 0.05$) iron uptake (32.0 $\mu g \cdot h^{-1}$) as compared to iron alone (71.9 $\mu g \cdot h^{-1}$). Furthermore, iron + pectin reduced ($P < 0.05$) iron uptake (28.5 $\mu g \cdot h^{-1}$) as compared to iron alone. They speculated that the hydroxyl groups of the fibers were responsible for binding iron by forming iron-lignin complexes that impaired intestinal absorption of iron.

Effects on Growth Performance

Dietary fiber reduces energy intake through nutrient dilution, and high levels of incorporation may decrease growth rate of dogs (Delorme et al., 1985). Five-month-old puppies fed diets containing 14.1 percent DDGS exhibited lower ($P < 0.05$) total tract digestibility of dry matter and gross energy compared to control animals consuming no DDGS (Allen et al., 1981). Although daily nitrogen excretion was greater ($P < 0.05$) for dogs consuming DDGS, nitrogen retention was similar between groups. This suggests that, even at a young age, dogs have the intestinal microbiota necessary to efficiently ferment the fiber in DDGS.

Monsan and Paul (1995) reported that the addition of small quantities (<1 percent) of nondigestible oligosaccharides to animal feeds can result in improvements in weight gain, feed intake, and health status of rabbits, pigs, and poultry. However, these effects varied greatly depending on the type of oligosaccharide, animal species and age, and rearing conditions. No data are available on how the growth of puppies or kittens specifically is affected by fermentable carbohydrates.

Effects on Reproductive Performance

Few data are available on the effects of fermentable carbohydrates on the reproductive performance of companion animals. Visek and Robertson (1973) fed gestating bitches a corn-soybean meal diet supplemented with 0, 20, or 40 percent dried brewer's grain (DBG), resulting in dietary NDF concentrations of 23.8, 29.2, and 31.9 percent, respectively. Numbers of puppies per litter and puppies born dead were similar among treatments. More females required assistance at whelping in the group consuming 20 percent DBG. This effect was not duplicated in the 40 percent DBG group, and the authors concluded that DBG is a satisfactory ingredient for gestating dogs.

Effects on Weight Control and Nutrition of the Obese Animal

Obesity is estimated to occur in 25 percent of dogs and cats in westernized societies (Burkholder and Toll, 2000). The incidence of obesity increases with age and is more frequent in neutered than intact animals (Sloth, 1992). In addition, cats are affected by obesity at an earlier age than are dogs (Scarlett et al., 1994). Both insoluble and soluble fibers have been used as a means of restricting energy intake for weight control in companion animal nutrition. Fiber dilutes the caloric content of food and offers an attractive solution for preventing weight gain in dogs and cats (Jewell et al., 2000). Dietary fiber was thought to encourage proper weight maintenance through regulation of appetite (Butterwick and Markwell, 1997; Jackson et al., 1997), simple mechanical interference and other physical effects, and complex hormonal interactions (Rossner, 1992) determined by the nature and type of fiber (Blundell and Burley, 1987). Pappas et al. (1989) demonstrated that gastric distension was a physiologic satiety signal in dogs.

Jewell and Toll (1996) found that a dog diet containing 21 percent crude fiber (as-fed basis) depressed dry matter and caloric intake compared to a diet containing <2 percent crude fiber. A subsequent study determined that dogs fed high-fiber food (19.4 percent crude fiber, as-fed basis) decreased energy consumption by 27 percent (implying satiety) and lost more than five times the fat mass of dogs fed low-fiber (1.7 percent, as-fed basis) food (Jewell et al., 2000). Dogs on the high-fiber diet lost 0.77 percent body fat per week, which falls in the accepted range of weight loss for dogs and cats on a weight loss program (0.5 to 2 percent of initial body weight per week) (Burkholder and Toll, 1999).

Jackson et al. (1997) fed low-fiber (14 percent TDF; 12 percent insoluble and 1.2 percent soluble fiber, as-fed basis) and high-fiber (29 percent TDF; 26 percent insoluble and 2.3 percent soluble fiber, as-fed basis) diets to dogs ($n = 30$) and found no differences in total daily food intake. However, total daily calorie intake was lower ($P < 0.05$) for dogs fed the high-fiber diet compared to dogs on the low-fiber diet (65.3 vs. 79.4 kcal·kg $BW^{-1} \cdot d^{-1}$, respectively). Conversely, Butterwick et al. (1994) did not detect any beneficial effects on food intake of dogs by including soluble or insoluble fiber in diets, since dogs had similar energy intakes.

Effects on the Geriatric Animal

The process of aging results in a progressive decline in organ function and adaptability. For example, dogs and cats become increasingly less able to regulate blood sugar concentrations as they age (Mosier, 1989; Sheffy et al., 1985). Banks (1981) found that older dogs required a longer period

for postprandial blood glucose concentrations to return to baseline values compared to young dogs. Fiber fermentation results in a blunted postprandial glucose response and enhances the action of insulin in the blood. While the underlying mechanism for this action is not fully understood, dietary fiber may nonetheless be useful in the management of dogs and cats diagnosed with mild hyperglycemia (Nelson, 1989).

Health-Related Characteristics

Gastrointestinal Tract Health

Table 4-8 summarizes the effects of nondigestible carbohydrates on gastrointestinal tract health. Sunvold (1996) reviewed the importance of carbohydrate fermentation in the colon for gut health in companion animals. Fermentative end products are dependent on the chemical composition of the starting substrate (Vickers et al., 2001). For example, fermentation of RS, fructooligosaccharides, or inulin results in an increased proportion of butyrate (Topping, 1999; Vickers et al., 2001). Kripke et al. (1989) postulated a trophic effect of SCFAs on intestinal function and metabolism, especially for butyrate. Butyrate is the preferred energy substrate for canine colonocytes (Drackley and Beaulieu, 1998) and likely plays a key role in normal colonocyte function, including cell proliferation, differentiation, and metabolism (Sakata, 1987; Scheppach et al., 1992).

Massimino et al. (1998) reported that dogs had longer ($P < 0.05$) jejunal villi (1,517 vs. 1,343 μm) and a higher ($P < 0.05$) uptake affinity (V_{max}) of D-glucose (182 vs. 133 nmol·mg^{-1} tissue per minute) when they were fed an isonitrogenous, isoenergetic diet containing 9.5 percent (as-fed basis) of a blend of fermentable fibers (6 percent sugar beet pulp, 2 percent gum arabic, and 1.5 percent fructooligosaccharide) than when they were fed a diet with a poorly fermented fiber (7 percent wood cellulose, as-fed basis). The putative beneficial health effects of fiber on the small intestine were attributed to the anaerobic fermentation of fiber in the lower gut resulting in SCFA production. Short-chain fatty acids are thought to mediate beneficial trophic effects on intestinal tissues proximal to the site of fermentation via hormonal or other signaling pathways (Sakata, 1987; Tappenden et al., 1997), although the exact mechanisms are poorly understood.

Hallman et al. (1995) supplemented dog diets with approximately 8.7 percent TDF supplied by divergent fiber sources (cellulose, beet pulp, or pectin + gum arabic) and found that dogs fed cellulose had lighter-weight ($P < 0.05$) colons (6.09 g·kg BW^{-1}) than did those fed beet pulp (6.52 g·kg BW^{-1}) or pectin + gum arabic (6.62 g·kg BW^{-1}). Dogs fed cellulose also had the highest incidence of colonic crypt mucus distension (71.4 percent) and cryptitis (41.4 percent) when compared to those fed beet pulp (46.7 percent and 20.0 percent, respectively) or pectin + gum arabic (53.3 percent and 20.0 percent, respectively). Further, dogs fed pectin + gum arabic had the highest incidence of exfoliation (46.7 percent) compared to those fed beet pulp (6.7 percent) or cellulose (7.1 percent). These data support the role of SCFAs from fermentable fibers in supporting normal colonic growth and metabolism.

In a study conducted by Buddington et al. (1999), adult beagles were fed diets containing 36 g·kg^{-1} cellulose or 42 g·kg^{-1} beet pulp + 10 g·kg^{-1} fructooligosaccharides as the fiber sources. Dogs fed beet pulp + fructooligosaccharides had longer (372 vs. 306 cm; $P < 0.05$) and heavier (430 vs. 318 g wet weight; $P < 0.05$) small intestines, with greater absorptive surface area (1,582 vs. 1,240 cm^2; $P < 0.05$). Furthermore, beet pulp + fructooligosaccharide supplementation increased ($P < 0.05$) proximal small intestinal total glucose uptake capacity by approximately 133 percent and numerically enhanced total proline uptake (10 percent). The researchers suggested that the increased small intestine size, absorptive area, and absorptive capacity of dogs consuming fructooligosaccharides was partially due to colonic fermen-

TABLE 4-8 Characteristics of Selected Carbohydrates and Their Effects on Gastrointestinal Health Characteristics of Dogs and/or Cats[a]

	Fiber Properties[b]		Animal Effects		
Fiber Type	Fermentability	Viscosity	Structure[c]	Function[d]	Prebiotic
Cellulose	N	N	↓ ↔	↔	N
Beet pulp	Y	N	↑	NI	NI
Pectin and gum arabic	Y	Y	↑	NI	NI
Beet pulp and FOS[e]	Y	N	↑	↑	NI
FOS[e]	Y	N	↑	↑	Y

[a]Abbreviations used: Y = yes; N = no; ↑ = increase; ↓ = decrease; ↔ = no effect; NI = no information available.
[b]The dietary fiber characteristics of fermentability and viscosity were chosen based on the recommendations of the Institute of Medicine (2001) as meaningful alternative labels for the terms soluble and insoluble fiber.
[c]Structure denotes changes in intestinal muscosa thickness, villus height, or crypt depth.
[d]Function denotes changes in intestinal nutrient transporters or nutrient absorption.
[e]Fructooligosaccharides.

tation of the fibers to SCFA and subsequent signaling of beneficial trophic mechanisms proximally in the intestine.

One possible mechanism underlying SCFA-mediated colonocyte proliferation is increased colonic blood flow. Howard et al. (1999) fed dogs meat-based diets supplemented with either cellulose (60 $g \cdot kg^{-1}$), fructooligosaccharides (15 $g \cdot kg^{-1}$), beet pulp (60 $g \cdot kg^{-1}$), or a fiber blend (60 $g \cdot kg^{-1}$ beet pulp, 20 $g \cdot kg^{-1}$ gum talha, 15 $g \cdot kg^{-1}$ fructooligosaccharides) to investigate the effect of SCFAs produced from fiber fermentation on intestinal blood flow. Dogs fed fructooligosaccharides had greater ($P < 0.10$) blood flow via the left colic artery than dogs fed cellulose or beet pulp. Additionally, fructooligosaccharide supplementation resulted in decreased cell proliferation and increased cell differentiation as assessed by shorter ($P < 0.10$) leading edges and smaller ($P < 0.05$) proliferation zones in the proximal colon. This suggests a role for fructooligosaccharides in maintaining normal colonic mucosal development, since neoplastic colonocytes exhibit rapid proliferation and decreased differentiation.

Intestinal transit time, which is affected by fermentable carbohydrates, plays a major role in determining the composition of colonic microflora. Cummings and Macfarlane (1991) reported that increased transit time is correlated with increased concentrations of protein fermentation end products (e.g., ammonia, phenols). Gibson and Roberfroid (1995) stated that most intestinal bacteria can be divided into species that exert detrimental effects (staphylococci, clostridia, and veillonella) or species that benefit the host (bifidobacteria, lactobacilli, and eubacteria). Diarrhea, infection, digesta putrefaction, and promotion of carcinogenesis are examples of pathogenic effects, while defense against pathogens, prevention of infection, and reduction of serum cholesterol are examples of beneficial effects (Gibson and Wang, 1994; Araya-Kojima et al., 1995).

The most adaptable method for altering colonic bacterial populations is the type of fermentative substrate supplied. Prebiotics are nondigestible oligosaccharides that selectively stimulate the growth and/or activity of a limited number of resident colonic beneficial bacteria (Gibson and Roberfroid, 1995). Prebiotic oligosaccharides include fructooligosaccharides, mannanoligosaccharides, glucooligosaccharides, galactooligosaccharides, and xylooligosaccharides.

Terada et al. (1992) supplemented 1.5 g lactosucrose per day to dogs, which increased ($P < 0.05$) the number of bifidobacteria and decreased ($P < 0.05$) the concentration of *Clostridium perfringens* in fecal samples. Lactosucrose supplementation also reduced ($P < 0.05$) concentrations of putrefactive compounds in feces (ammonia, phenol, indole, skatole, and ethylphenol). Similarly, Terada et al. (1993) reported that supplementing cats with 175 mg lactosucrose per day decreased ($P < 0.05$) fecal concentrations of *Clostridium perfringens* but increased ($P < 0.05$) concentrations of lactobacilli and incidence ($P < 0.05$) of bifidobacteria, indicating an improvement in colonic microflora.

Sparkes and coworkers (1998b) reported positive effects of fructooligosaccharide supplementation on cats. Dietary fructooligosaccharides (0.75 percent, DM basis) increased fecal concentrations of lactobacilli (164-fold; $P < 0.05$) and bacteroides (13.2-fold; $P < 0.05$) and decreased fecal concentrations of *Escherichia coli* (75 percent; $P < 0.05$) and *Clostridium perfringens* (98 percent; $P = 0.08$). However, when fructooligosaccharides, xylooligosaccharides, or mannanoligosaccharides were supplemented (0.5 percent of the diet) to dogs, fecal concentrations of *Escherichia coli* and lactobacilli were unaffected (Strickling et al., 2000). *Clostridium perfringens* tended ($P = 0.09$) to be lower in the feces of dogs supplemented with mannanoligosaccharides.

In addition to improving colonic microbial populations, prebiotic oligosaccharides also may positively affect small intestinal bacteria. Feeding 1 percent fructooligosaccharides (as-fed basis) decreased ($P < 0.05$) the number of aerobic and facultative anaerobic bacteria in the small intestine of German shepherd dogs susceptible to small intestinal bacterial overgrowth (Willard et al., 1994). However, 0.75 percent dietary fructooligosaccharides (DM basis) did not affect duodenal bacteria concentrations in healthy cats (Sparkes et al., 1998a).

Glycemic Control

In the small intestine, viscous NSPs act as a barrier to the release of nutrients and slow their absorption (Eastwood, 1992; Annison and Topping, 1994), which is important in the control of glucose and insulin metabolism (Crapo et al., 1976). Blunted glycemia may occur by prolonging gastric emptying and intestinal transit time, slowing starch hydrolysis, and delaying glucose absorption (Nelson, 1989; Graham et al., 1994).

Nguyen et al. (1994) reported that diet composition influences postprandial glycemia. One dry diet (D: 3.3 percent crude fiber, 48.4 percent nitrogen-free extract) and three canned diets (C1: 2.4 percent crude fiber and 15.5 percent nitrogen-free extract; C2: 2.1 percent crude fiber and 47.1 percent nitrogen-free extract; C3: 10.8 percent crude fiber and 35.2 percent nitrogen-free extract) were tested in healthy adult dogs. After a single meal, only diet C3 resulted in a reduced ($P < 0.05$) area under the insulin curve and a lower ($P < 0.05$) relative insulinemic index. No relationship was found between crude fiber content of the diet and blood glucose or insulin. This was attributed to the inability of the crude fiber analysis to recover soluble dietary fibers, which can play a key role in mediating postprandial hyperglycemia. A subsequent study by Nguyen et al. (1998) measured normal canine glycemic and insulinemic responses to 20 experimental foods (15 dry and five canned) with a wide range of concentrations (DM basis) of TDF (3.2 to 39.1 percent), insoluble fiber (3.2 to 32.3 percent), soluble fiber (0.4 to 4.7 percent), and starch (0.4 to 52.7 percent). A linear correlation between starch content of the foods and glucose response area was

shown. However, variations in total, soluble, or insoluble fiber did not account for the responses observed.

Diez et al. (1998) fed dogs corn-based diets containing 7 percent (DM basis) sugar beet fiber, guar gum, or inulin. Both guar gum and SBF delayed the onset of hyperglycemia (40 minutes) as compared to inulin or the control (20 minutes). Consumption of guar resulted in higher ($P < 0.05$) fasting glucose concentrations than any other treatment. Insulin concentrations were not significantly affected by diet.

Massimino et al. (1998) studied the effects of chronic ingestion of fermentable DF (60 $g \cdot kg^{-1}$ sugar beet pulp + 20 $g \cdot kg^{-1}$ gum arabic + 15 $g \cdot kg^{-1}$ fructooligosaccharides, as-fed basis) vs. nonfermentable DF (70 $g \cdot kg^{-1}$ cellulose, as-fed basis). Dogs consuming the fermentable fiber blend had greater glucagon-like-peptide (GLP-1) concentrations in mucosal scrapings (41 ± 4 pmol GLP vs. 25 ± 4 pmol [$P < 0.05$]) for dogs on the low fermentable fiber source (wood cellulose) diet. GLP-1 acts as an insulin secretogogue in humans. However, DF type did not influence dog blood glucose concentrations at any time (0, 15, 30, 45, 60, 90, or 120 minutes) after an oral glucose load of 2 g·kg BW^{-1}.The authors concluded that ingestion of fermentable fibers can improve glucose homeostasis.

Immune Function

Field et al. (1999) studied the effects of fermentable fiber on the immune system of dogs. Meat-based diets were supplemented with either 60 $g \cdot kg^{-1}$ sugar beet pulp + 20 $g \cdot kg^{-1}$ gum arabic + 15 $g \cdot kg^{-1}$ fructooligosaccharides, as-fed basis (fermentable mixture) or 70 $g \cdot kg^{-1}$ cellulose (as-fed basis; nonfermentable mixture). As compared to the nonfermentable diet, fermentable fiber decreased ($P < 0.05$) the proportion of Ig+ cells and increased the CD4/CD8 (T-helper:cytotoxic T cell) ratio in the peripheral blood. An increase in this ratio is associated with an alteration in mitogen response. Accordingly, in this study, fermentable fibers variably increased mitogen response in lymphoid organs but did not affect mitogen responses in peripheral blood. The authors concluded that fermentable fibers alter gut-associated lymphoid tissue but do not greatly impact type and function of immune cells in peripheral blood.

Mannanoligosaccharides may alter the immune system. Mannanoligosaccharides are thought to act by preventing the binding of lectins to gut epithelial cells and have been reported to increase neutrophil activity in dogs (O'Carra, 1997). Adult dogs were fed dry diets containing 0, 0.1, 0.2, or 0.4 percent mannanoligosaccharides but did not exhibit detectable systemic immune responses, since there was no change in plasma IgG concentration. In 6-week-old puppies fed diets supplemented with 0.2 percent mannanoligosaccharides, the number of circulating neutrophils in the blood were numerically increased in response to vaccination (28 percent greater on day 14 and 60 percent greater on day 21) as compared to vaccinated puppies receiving a control diet (O'Carra, 1997). Again, there was no significant effect on plasma IgG measurements. Swanson et al. (2002a) supplemented adult dogs with 2 g mannanoligosaccharides, fructooligosaccharides, or mannanoligosaccharides and fructooligosaccharides each day. After 14 days of consumption, mannanoligosaccharide-supplemented dogs exhibited enhanced systematic immune status as evidenced by increased number of lymphocytes as percentage of white blood cells and a numerical increase in serum immumoglobulin IgA. Dogs supplemented with mannanoligosaccharides plus fructooligosaccharides demonstrated increased IgA concentrations in ileal effluent, indicating enhanced local immunity. In a follow-up study, dogs fed 2 g fructooligosaccharides plus 1 g mannanoligosaccharides each day did not exhibit increased IgA concentrations in blood, ileal effluent, or feces (Swanson et al., 2002b), suggesting that the immune-enhancing ability of mannanoligosaccharides is dependent, in part, on age and health status of the animal.

POORLY FERMENTABLE CARBOHYDRATES (CELLULOSE AND WHEAT BRAN)

Presence in Foodstuffs

Cellulose is the most abundant plant polysaccharide on earth. It accounts for 15 to 30 percent of the dry mass of all primary plant cell walls (McNeil et al., 1984) and is found in most plants such as vegetables, sugar beets, and various brans (Meyer and Tungland, 2001). In terms of nonfermentable carbohydrates specifically, wheat bran is composed of 37.3 percent cellulose, 55.2 percent hemicelluloses, and 10.5 percent lignin (Meuser et al., 1985).

Digestion, Absorption, and Utilization

Morris et al. (1977) reported a negative apparent cellulose digestibility coefficient (–0.007 percent) for cats fed a meat-based diet supplemented with cellulose. In this experiment, diets were prepared by mixing cellulose with the basal diet (1:7 w/w). Sunvold et al. (1995b,c) measured fiber digestibility by dogs and cats by using an in vitro fermentation system. Isolated wood cellulose organic matter disappearance was the lowest (<10 percent) of all fibers tested with either dog or cat fecal inoculum. These results were confirmed in vivo when TDF digestibility by dogs fed 7.5 percent supplemental TDF as isolated wood cellulose was lower (11 percent) than TDF digestibility for dogs fed beet pulp, citrus pulp, or a combination (80 percent beet pulp, 10 percent citrus pectin, 10 percent guar gum) blend (29.0, 43.0, and 51.3 percent, respectively). Increasing cellulose from 0 to 20 percent in cat diets also reduced organic matter digestibility from 86 to 68 percent (Brown, 1989).

Compared to a meat-based control diet containing no supplemental fiber, consumption by dogs of a diet containing 12.8 percent wheat bran resulted in a reduction in dry

matter (87.6 vs. 83.1 percent), organic matter (90.2 vs. 86.3 percent), and NDF (57.2 vs. 41.6 percent) digestibilities (Fahey et al., 1990a). Stock-Damge et al. (1983) demonstrated that diets supplemented with 5 $g \cdot d^{-1}$ of wheat bran fed to dogs increased the flow rate of pancreatic secretions, bicarbonate, and amylase into the intestinal tract. Stock-Damge et al. (1983, 1984) also found that secretin administered intravenously altered the flow rate of pancreatic secretions and suggested that wheat bran may have altered the flow rate of pancreatic secretions by altering endogenous secretions of secretin.

Factors Affecting Digestibility, Absorption, and Utilization

Normal extrusion conditions may facilitate redistribution of insoluble to soluble fiber (Camire et al., 1990). However, since nonfermentable carbohydrates contain mostly insoluble fiber, it is unlikely that this occurs for cellulose and wheat bran.

Nutritive Value

Depending on the extent of fermentation, carbohydrates have an energy value of 0 to 2.4 $kcal \cdot g^{-1}$ (10.04 $kJ \cdot g^{-1}$) in monogastric species (Roberfroid, 1993; Molis et al., 1996). Since neither cellulose nor wheat bran is extensively fermented, their energetic contribution is thought to be minimal to none.

Physicochemical Effects

Because of its β-1,4-linkage, cellulose crystallizes in a linear configuration, with a high degree of intermolecular hydrogen bonding. This gives it substantial shear and tensile strength. The cellulose derivative carboxymethylcellulose is resistant to the effects of acid and salt. It has a superior stability in baked goods and sauces, and can withstand extreme processing conditions such as extended heating and high shear processing. Methylcelluloses are strong film formers and can serve as binders in food matrices (Prosky and DeVries, 1992).

Water-Binding Capacity

Insoluble fibers such as cellulose are only poorly fermented once they reach the colon. Water retention characteristics of these fibers exert a stool-bulking effect that causes shorter transit times and increased fecal mass (Meyer and Tungland, 2001). Powdered cellulose can retain about 3.5 to 10 times its weight in water. The water-binding capacity of powdered cellulose is directly related to its average fiber length. Commercial forms of powdered cellulose for food application are available in fiber lengths ranging from 22 to 290 μm. The water-binding capacity of cellulose increases as fiber length increases. The water-binding capacity of wheat bran is similar to that of cellulose and also is highly affected by particle size (Dreher, 1999). In addition, the type of wheat can affect the water-binding capacity of wheat bran. The water-binding capacity of the bran of soft white wheat is 1.1 $g \cdot g^{-1}$, while that of hard red wheat is 4.5 $g \cdot g^{-1}$ (Dreher, 1999).

Viscosity

Colloidal cellulose gel products can increase the viscosity of sugar solutions at concentrations less than 1 percent (Dreher, 1999). Reppas et al. (1991) administered 500-mL solutions of 0.9 percent sodium chloride and 0.8 percent polyethylene glycol (PEG) as a volume marker by orogastric tube to dogs. Viscosity of the solutions was increased by addition of different amounts (2.0 or 3.3 percent) of hydroxypropylmethylcellulose. The lag time of PEG recovery at the duodenum and mid-jejunum increased linearly as a function of viscosity. These researchers concluded that the ability of water-soluble fibers to control absorption rate of nutrients from the gut could contribute to an increase in luminal viscosity and a decrease in rate of transit.

Bulking Capacity

Powdered cellulose is commonly used as a noncaloric bulking agent in reduced-calorie foods (Ang and Miller, 1991).

Physiological Effects

Effects on Food Intake, Transit Time, and Fecal Excretion

Numerous studies have demonstrated an increase in stool weight and a decrease in transit time due to cellulose supplementation of human diets (Stephen, 1989). Dobenecker and Kienzle (1998) supplemented incremental concentrations of cellulose in dogs fed a meat-based diet in an effort to determine the fiber concentration at which food intake decreased. Dogs fed higher-fat diets tolerated more fiber (41.8 percent crude fiber) compared to lower-fat meat or chicken meal diets (30.8 and 31.9 percent crude fiber, respectively).

Wheat bran, an ingredient rich in hemicelluloses, cellulose, and lignin, affects transit time (Payler et al., 1975; Wyman et al., 1976) and stool weight, moisture, and composition (Stephen and Cummings, 1980) in humans. Addition of 30 g of either wheat bran or cellulose increased duration of the postprandial pattern of intestinal motility by 41 to 54 percent in the duodenum of dogs. Addition of wheat bran also increased transit time by 28 percent, while cellulose caused a 900 percent increase in transit time and a 50

percent reduction in flow of digesta in dogs (Bueno et al., 1980). In contrast, Burrows et al. (1982) reported that dogs fed a diet containing 9 percent α-cellulose had decreased intestinal transit time compared to dogs not consuming supplemental fiber (28.7 vs. 37.4 hours).

Stool weight reflects residual fiber and adherent bacteria (Kritchevsky, 1988). Cellulose results in a decreased fecal nitrogen concentration compared to highly fermentable fibers such as pectin, sugar beet, and soy bran (Tetens et al., 1996). Burrows et al. (1982) found that fecal weight and water content increased linearly as the supplemental α-cellulose concentration of dog diets increased from 3 to 6 to 9 percent.

Effects on Availability of Other Nutrients

Muir et al. (1996) found no differences in digestion of dry matter, organic matter, crude protein, TDF, or gross energy at the distal ileum of dogs fed beet pulp versus cellulose and pectin-containing diets. However, fat digestion was decreased ($P < 0.10$) for dogs fed 7.5 percent beet pulp compared to dogs fed a low-cellulose mixture (2.5 percent cellulose + 5 percent pectin), high-cellulose mixture (5 percent cellulose + 2.5 percent pectin), or 7.5 percent cellulose. In contrast, Earle et al. (1998) found that the apparent digestibility of organic matter and gross energy correlated negatively with dietary cellulose content for both dogs ($r = -0.88$ and -0.88, respectively) and cats ($r = -0.92$ and -0.87, respectively). In addition, Burrows et al. (1982) found that dry matter, protein, and fat digestibilities decreased linearly when increasing concentrations (3, 6, and 9 percent) of α-cellulose were incorporated into meat-based dog diets. The regression estimate of true digestibility for α-cellulose was 6 percent.

Sunvold et al. (1995b) measured lower dry matter (81.0 percent) and organic matter (83.5 percent) digestibilities by cats consuming cellulose-containing diets, and higher dry matter (88 percent) and organic matter (91.6 percent) digestibilities by cats fed diets containing no supplemental fiber. However, nitrogen and lipid digestibilities by cats fed cellulose-containing diets were higher (88.4 and 95.0 percent, respectively) compared to diets with no fiber added (86.7 and 93.9 percent, respectively).

Zentek (1996) compared the effects of 10 percent cellulose, pectin, or guar gum on apparent nutrient digestibilities by dogs. The apparent digestibility of dry matter by dogs fed the cellulose diet was lower (80.3 ± 2.0 percent) than for the pectin (89.6 ± 1.7 percent) or guar gum (88.1 ± 1.3 percent) diets. In addition, dogs fed the cellulose-containing diet had a lower sodium absorption (86.4 ± 4.2 percent) compared to dogs fed either the pectin (95.2 ± 2.4 percent)—or the guar gum (94.1 ± 2.1 percent)—containing diets. Wheat bran has been shown to affect mineral excretion by humans, although most of the effects are thought to be due to its phytate content and not NSPs (Stephen, 1989).

Kienzle et al. (1991) reported that cats consuming diets containing 10 percent wheat bran, 15 percent horn meal, 15 percent feather meal, or 15 percent dried grass meal had decreased protein (>3 percentage units) and/or lipid (0 to 11 percentage units) digestibilities than animals fed a diet without these components. In experiments with dogs, Muir et al. (1996) found that amino acid digestion at the distal ileum was not affected by dietary cellulose, except for lysine, which increased from 68.2 percent for dogs fed a low-cellulose mixture (2.5 percent cellulose + 5 percent pectin) to 83.5 percent in dogs fed a 7.5 percent cellulose diet. Further, these authors found that dogs fed the low-cellulose mixture had lower apparent ileal digestibility values compared to dogs on the high-cellulose mixture (5.0 percent cellulose + 2.5 percent pectin) for dry matter (64.1 vs. 74.0 percent), organic matter (71.5 vs. 79.2 percent), crude protein (66.1 vs. 76.7 percent), fat (93.8 vs 96.1 percent), TDF (–22.3 vs. –8.1 percent), and gross energy (76.3 vs. 82.8 percent).

Effects on Growth Performance

Delorme et al. (1985) evaluated the effect of 6 or 12 percent supplemental wheat bran diets fed to female beagle puppies. Addition of wheat bran up to 16 percent dietary NDF did not affect growth, food intake, or food efficiency, but, when wheat bran addition exceeded 22 percent dietary NDF in a 22 percent crude protein diet, animals were unable to adapt fully to the dilution of their diets, leading to reduced growth and food efficiency.

Effects on Weight Control and Nutrition of the Obese Animal

Both insoluble and soluble fibers have been used as a means to restrict energy intake by companion animals. Butterwick et al. (1994) found that adding 2 percent wheat bran or α-cellulose to a low-calorie, meat-based commercial diet had no effect on satiety in dogs, as measured by intake of a challenge meal offered 3 hours after introduction of the test diet, when fed at an energy intake that allowed for weight reduction. These results were confirmed when either 4 or 7 percent α-cellulose was incorporated into commercial low-energy diets (Butterwick and Markwell, 1997).

Health-Related Characteristics

Gastrointestinal Tract Health

Diets high in fiber are thought to be a factor in prevention of conditions such as diverticular disease (Smith et al.,

1981). Coarse wheat bran increased ($P < 0.01$) stool weight and decreased ($P < 0.05$) intestinal transit time to a greater extent than finely ground wheat bran from the same source in human patients with diverticular disease.

CARBOHYDRATES IN DOG AND CAT DIET FORMULATIONS

The recommended carbohydrate content of diets depends on amount of food consumed, caloric density of the food, and energy requirement of the animal (Meyer and Kienzle, 1991). Cereal grains are carbohydrate-rich ingredients used in formulating cat and dog foods. These ingredients are included at different dietary concentrations depending on diet type.

Adult dogs have a jejunal lactase activity of 33 $U \cdot g^{-1}$protein and tolerate lactose at approximately 3 $g \cdot kg\ BW^{-1} \cdot d^{-1}$ (Meyer and Kienzle, 1991). For this reason, lactose content of the adult dog diet should be limited. In contrast, puppies have high lactase activity (96 $U \cdot g^{-1}$ protein) and are able to digest, absorb, and metabolize lactose (Kienzle, 1993d). Bennett and Coon (1966) observed immediate diarrhea and malaise in dogs when lactose furnished 54 percent of the calories in the diet. Burger (1993) reported that dogs tolerate lactose at concentrations of 5 percent or less of total energy.

Due to their lack of pancreatic amylase, suckling puppies and kittens should not be given milk substitutes containing starch (Meyer and Kienzle, 1991). By the time puppies can consume appreciable amounts of solid food, they can efficiently use calories from fat and nonstructural carbohydrates such as starch (Hintz, 1988), although an optimal ratio of fat to nonstructural carbohydrates in puppy foods is unknown. Cats have a limited capacity to metabolize certain sugars. Kienzle (1994) observed signs of toxicity in cats at relatively low intakes of galactose (5.6 $g \cdot kg\ BW^{-1} \cdot d^{-1}$).

Kienzle (1993d) speculated that cats are unable to adapt to increased concentrations of dietary carbohydrates since the activities of disaccharidases in the small intestinal mucosa are not affected by the diet of adult cats. Although the cat depends on gluconeogenesis to meet much of its daily energy needs (Tarttelin, 1991), there is evidence that cats effectively utilize dietary glucose from starch digestion (Kienzle, 1993a,b). Tarttelin (1991) suggested that feeding too high a concentration of carbohydrate may induce feline urologic syndrome since any persistent increase in urine pH, such as that induced by ingestion of high carbohydrate concentrations, results in precipitation of magnesium ammonium phosphate crystals (struvite). This may lead to blockage of the urethra and predispose the cat to dietary induced feline urologic syndrome (Tarttelin, 1991). There is no known optimal starch inclusion level for the cat diet.

The fiber content of various companion animal diets is quite variable. Plant-based diets often contain a considerable amount of fiber. For example, corn and wheat grains contain approximately 9 and 18 percent TDF, respectively (Fahey, 1995). Conversely, rice contains only 3 percent TDF (Fahey, 1995). By-products (e.g., corn gluten feed, soybean hulls) and purified fiber sources (e.g., wood cellulose) often are included in pet diets and contribute varying amounts of fiber.

Utilization of high-fiber diets is dependent on the animal's life stage. Anecdotal information exists, suggesting that animals with no apparent health problems can grow and reproduce with as much as 15 to 20 percent TDF in their diets (Fahey, 1995). However, supplementing a bitch's diet with insoluble fiber during the latter phases of pregnancy and during lactation should be avoided since it will decrease the energy density of the diet, potentially increasing the intake necessary to meet energy needs beyond physical capacity. Fiber can be used during this time if indicated for constipation (Moser, 1992).

The appropriate use of fiber in weight reduction diets is of particular concern. Fiber content is not central to a low-calorie diet; rather, caloric intake of the animal per unit of time (Brown, 1990) is the key issue. The typical crude fiber concentration in dry petfood is 2.5 to 4.5 percent, but its concentration in some reduced-calorie diets may be 9 to 10 percent. Use of these high concentrations of fiber in weight reduction diets may allow the animal to achieve a sense of fullness without a high energy intake (Brown, 1990).

Companion animal longevity is important to pet owners and is affected by many factors, including diet. The purpose of diets specifically formulated for geriatric animals is to ameliorate or avoid the effects of aging that are impacted by nutrition (Markham and Hodgkins, 1989). In the geriatric animal, a small amount of dietary fiber facilitates the desired caloric restriction and aids intestinal function (Markham and Hodgkins, 1989). Although it is not a required nutrient, dietary fiber is directly involved in maintaining gut health through provision of SCFAs, maintaining a healthy gut microflora, and possibly even preventing diseases.

The question has been raised of how much dietary fiber is too much. Although no simple answer exists, it has been demonstrated earlier in this chapter that high fiber concentrations in companion animal diets can decrease the digestibility of other nutrients. In addition, numerous fiber sources exist for companion animal diet supplementation, and not all fibers are equal in terms of their physiological effects. One source that has been shown to provide good stool characteristics without significantly decreasing nutrient digestibility is beet pulp (Fahey et al., 1990a,b; Sunvold et al., 1993). Beet pulp contains both insoluble and soluble fiber components in a desirable ratio (approximately 17 to 20 percentage units of soluble fiber; Fahey, 1995). Additional examples of beneficial fibers are provided in Tables 4-7 and 4-9.

For many carbohydrate sources, there exists sufficient data to establish a level of dietary inclusion at which no adverse effects can be expected. The safe upper limit (SUL) of dietary inclusion for various carbohydrates is listed in Table

TABLE 4-9 Safe Upper Limits of Selected Carbohydrates for Adult Dog and Cat Maintenance Diets (g·kg diet^{-1}, DM basis)

Item	Dogs	Cats	Reference(s)
Glucose	ND	50-150	Drochner and Muller-Schlosser, 1980; Meyer and Kienzle, 1991
Sucrose	350	50-150	Drochner and Muller-Schlosser, 1980; Meyer and Kienzle, 1991
Lactose	100	50	Drochner and Muller-Schlosser, 1980; Meyer and Kienzle, 1991
Cooked corn starch	ND	240	Meyer and Kienzle, 1991
Cooked corn flour	436[a]	ND	Murray et al., 1999
Cooked potato flour	504[a]	ND	Murray et al., 1999
Cooked rice flour	441[a]	ND	Murray et al., 1999
Cooked wheat flour	491[a]	ND	Murray et al., 1999
Raffinose/stachyose	50	50	Meyer and Kienzle, 1991
Fructooligosaccharides	40[b]	7.5[a]	Diez et al., 1997a; Sparkes et al., 1998b; Strickling et al., 2000
Inulin	70[a]	ND	Diez et al., 1998
Mannanoligosaccharides	5.9[a]	ND	Strickling et al., 2000; Zentek et al., 2002
Xylooligosaccharides	5[a]	ND	Strickling et al., 2000
Transgalactooligosaccharides	5.9	ND	Zentek et al., 2002; Diez et al., 1997a; Kienzle et al., 1991; Sunvold et al., 1995b
Cellulose	94[a]	100	Sunvold et al., 1995c; Zentek, 1996
Guar gum	34	ND	Diez et al., 1997a; Diez et al., 1997b; Zentek, 1996
Pectin	34	ND	Diez et al., 1997a; Zentek, 1996
Beet pulp	75	ND	Fahey et al., 1990b, 1992
Wheat bran	128	100	Fahey et al., 1990a; Kienzle et al., 1991
Peanut hulls	67[a]	ND	Fahey et al., 1990a
Tomato pomace	87[a]	ND	Fahey et al., 1990a
Oat fiber	75[a]	ND	Fahey et al., 1992
Fiber blend[c]	83[a]	83	Sunvold et al., 1995b,c

NOTE: ND = no experimental data available.
[a]Higher levels not experimentally tested.
[b]When mixed with sugar beet fiber in a 4:1 ratio.
[c]Mixture of Solka Floc and gum arabic in a 3:1 ratio.

4-9. Values presented are only for adult animals at maintenance. Adverse effects taken into consideration include, but are not limited to, occurrence of loose stools, elevated fecal water content, frequent defecation, marked reduction of nutrient digestibility, poor diet acceptability or palatability, and disturbances in nutrient metabolism. For example, Fahey et al. (1990b) supplemented dog diets with graded levels of beet pulp (0, 2.5, 5.0, 7.5, 10.0, and 12.5 percent, DM basis). At 10.0 or 12.5 percent inclusion, beet pulp resulted in more frequent defecation, a large increase in wet fecal volume, and a marked decrease in fecal DM percentage. Therefore, SUL for beet pulp in adult dog diets was set at 7.5 percent. However, studies investigating dose-responses are not available on all ingredients used in companion animal diets. In this situation, the SUL is set as the highest level tested that did not result in adverse effects. Occasionally, data do not exist to indicate a safe limit for inclusion of certain ingredients. An example of this is illustrated by a study with cats clearly showing that digestive disorders occurred when approximately 9.5 percent TDF was added to a diet as a fiber blend (35 percent citrus pectin, 30 percent locust bean gum, 20 percent carob bean gum, and 15 percent guar gum). The authors attributed the poor performance of these cats to several possible factors, including the rapidly fermentable nature of the fibers promoting bacterial overgrowth in the small intestine, decreased intestinal pH resulting in reduced activity of pancreatic enzymes, reduced activity of pancreatic enzymes by citrus pectin, and reduced nutrient absorption due to the viscous nature of the fibers (Sunvold et al., 1995). Since no lower concentrations of this fiber blend were tested, no SUL can be established.

For glucose and sucrose, there exists a range of SULs in cat diets due to conflicting data presented in the literature. This disparity may be attributed to differences in basal diet composition, because Drochner and Muller-Schlosser (1980) fed a plant-based diet, whereas Meyer and Kienzle (1991) fed meat-based diets. Therefore, basal diet composition also is an important consideration when interpreting SUL and/or desirable concentrations of ingredients that contain carbohydrate.

Different carbohydrates have varying physiological effects. Although few data exist for cats, there is considerable evidence suggesting that fermentable substrates are useful to dogs. When considering digestible or nondigestible carbohydrate inclusion in companion animal diets, it is critical to evaluate carefully the unique characteristics of all categories of carbohydrates used. Although SULs for many carbohydrates have been suggested, much more information is needed before minimum requirements (MRs) and recommended allowances can be established for the categories of carbohydrates discussed in this chapter.

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5

Fat and Fatty Acids

IMPORTANCE OF DIETARY FATS AND FATTY ACIDS

Fats are an important component of companion animal diets. Dietary fats provide a concentrated source of energy for storage and utilization and supply the essential fatty acids (EFAs) that are not otherwise synthesized. All fatty acids, including the EFAs, serve structural functions and their degree of unsaturation imparts specific fluid properties to cell membranes. Several polyunsaturated fatty acids (PUFAs) serve as precursors of prostaglandins and other eicosanoids, which are powerful physiologic regulators of cell functions. Dietary fats generally improve palatability and add an acceptable texture to foods beyond their provision of EFAs. They also serve as carriers for fat-soluble vitamins and thus provide important substrates for cell processes during all life stages.

Fats belong to a broader group of compounds known as lipids that can be glycerol or non-glycerol based. Glycerol-based lipids include simple lipids such as the hydrophobic triacylglycerols (triglycerides) and compound lipids that are more polar (phospholipids and glycolipids). Cholesterol and its fatty acid esters are non-glycerol-based lipids, and this category includes waxes, cerebrosides, terpenes, sphingomyelins, and various sterols.

TYPES AND SOURCES OF DIETARY FATS AND FATTY ACIDS

Nomenclature

Lipids are a diverse group of substances that have both structural and functional roles. Dietary lipids consist of free fatty acids linked either to a glycerol backbone as triacylglycerols or phospholipids or to a plant or animal alcohol such as cholesterol or retinol. In mammals, fatty acids may be saturated or unsaturated, with or without double bonds, respectively, but all are straight-chain hydrocarbon molecules. Saturated and monounsaturated fatty acids can be derived from the diet or synthesized by the animal body. Dietary unsaturated fatty acids may have their double bonds in either *cis* or *trans* configurations depending on fat source. However, the EFAs of mammals are polyunsaturated (i.e., two or more double bonds), straight-chain hydrocarbons with their important double bonds in a methylene-interrupted *cis* configuration that is required for EFA activity (Mead, 1980; Gurr, 1984). The presence of a *trans* double bond in a fatty acid is not incompatible with EFA activity as long as the basic pattern of a methylene-interrupted double-bond sequence of the *cis, cis* type is also present. Fatty acids are typically named either for the number of carbon atoms they contain and number of double bonds or after their parent molecule (Figure 5-1). Designation of the double-bond placement depends on the point of reference used in the molecular structure. The usual chemical convention is to number the carbon atoms from the functional group (in this case the carboxyl group) onward. Using this system, linoleic acid has double bonds between carbons 9 and 10 and 12 and 13 and is designated Δ9,12-18:2. This notation is referred to as the Δ-notation. It numbers the carbon atoms from the carboxyl terminus and indicates the location of each double bond. *Cis* and *trans* double bonds are designated with either a "c" or "t" in front of the number of the carbon where the double bond is located and the "Δ" symbol may not be used, such as c9,t12-18:2.

Fatty acid structures can also be specified using the ω-notation in the form of A:Bn-C (or A:Bω-C), where A is the number of carbon atoms in the chain, B is the number of double bonds, and C is the position of the first double bond from the methyl terminus. All double-bond placements are specified by this notation because it is applied only to straight-chain fatty acids having methylene-interrupted double bonds in their structure. Thus, linoleic acid is referred to as 18:2n-6 (or 18:2ω-6). Placement of the first double bond is between carbons 6 and 7 counted from the methyl terminus. Because the double bonds occur in methylene-interrupted sequence, only the first double-bond position has to

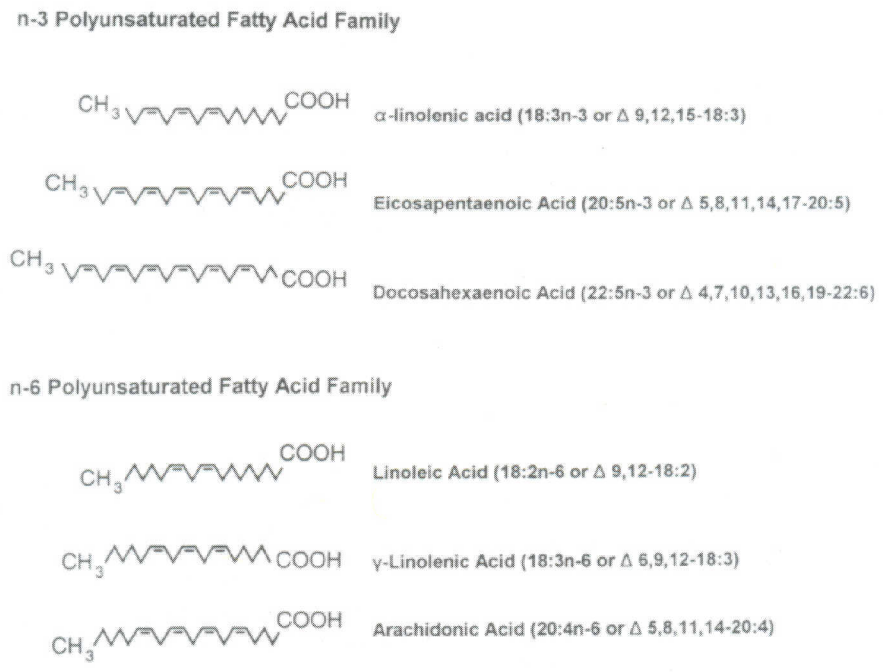

FIGURE 5-1 Chemical structure of the n-3 and n-6 polyunsaturated fatty acid families.

be stipulated. Strictly speaking, the ω-notation only applies to cis-unsaturated double bonds.

Each nomenclature has its advantages, and both are used. The Δ-notation readily demonstrates fatty acid regulation because desaturase activities are specific for double-bond placement from the carboxyl end. By contrast, the ω-notation shows the relationship within a specific fatty acid family and highlights metabolic relationships as a result of chain elongation and desaturation reactions that may occur. Appreciation of both nomenclatures provides a better understanding of the possible metabolic conversions involved.

Sources

The materials from which dietary fats are derived are primarily the storage fats of land and marine animals and the seed oils of numerous plants. The composition of storage fats derived from monogastric land mammals (e.g., dogs, cats, pigs, poultry) generally reflects the diets fed these animals. However, animals used for food production are generally fed low-fat diets based on grains. As such, the majority of tissue fatty acids are produced de novo from carbohydrates. Thus, their storage fats are primarily of the saturated and monounsaturated fatty acid type. When fats high in either linoleic acid (LA; e.g., soybean, corn, sunflower, safflower oils) or α-linolenic acid (ALA; e.g., linseed oil) are included, higher percentages of the respective PUFA in tissue lipids will result (Gurr, 1984; Campbell and Dorn, 1992; Campbell and Roudebush, 1995; Pawlosky et al., 1997; Waldron, 1999). This effect is similar in ruminants, although not to the same extent as a result of microbial hydrogenation of unsaturated fatty acids in the rumen prior to absorption. Thus, only modest changes in fatty acid composition of adipose tissue occur when feeding unprotected fats rich in PUFAs to ruminant animals. As might be expected, some *trans* fatty acids also are seen in ruminant species. Fats derived from marine life sources such as fish, phytoplankton, and other marine plants typically contain higher amounts of the n-3 type fatty acids than do land mammals. It should be noted that fish oils differ in composition between species and vary according to diet, seasonal influences, and habitat. In addition to high n-3 fatty acid content, some species contain reasonable amounts of long-chain monounsaturated fatty acids as well as saturated acids. Given the lack of equivalence among these sources, a clear picture of the types and amounts of specific n-3 fatty acids desired in a finished food product should be kept in mind when selecting from among them.

The oils derived from vegetable sources are comprised primarily of triacylglycerols and are found in both the seeds (e.g., soybean, corn) and, in some cases, the fleshy fruit (e.g., olive, palm). Leaf tissues of terrestrial plants contain reasonably high amounts of ALA (18:3n-3). However, these latter plant materials are low in total fat and generally do not constitute a major dietary source of fats for dogs and cats. Seed oils vary widely in their fatty acid composition, and a given fatty acid often predominates as characteristic of its particular plant origin. Thus, seed oils may be rich in either

18-carbon n-6 fatty acids or 18-carbon n-3 fatty acids, and some will contain varying amounts of both. The n-6 PUFAs including LA (18:2n-6) and γ-linolenic acid (GLA, 18:3n-6) are readily obtained from terrestrial animal and plant seed sources (see Table 13-3).

Trans Fatty Acids

When fat is added as a separate ingredient in manufactured foods for dogs and cats, it has typically undergone some type of extraction and partial purification process that may modify its overall composition. In some cases such as hydrogenation, more extensive changes in composition may occur especially because of the introduction of *trans* double bonds. Hydrogenation of fats and oils reduces the degree of unsaturation by adding hydrogen atoms to the carbon-carbon double bonds, thereby increasing their melting points and making them less susceptible to oxidative deterioration. This process is used primarily in manufacturing human food to achieve certain desirable characteristics of specific products. Hydrogenation is carried out using a finely powdered metal catalyst at moderately high temperatures and then the catalyst is removed. As hydrogenation occurs, some of the *cis* double bonds in the natural fatty acids are isomerized to the *trans* configuration. In addition, there is a migration of some double bonds along the length of the chain. Because the hydrogenation process is rarely taken to completion, the resultant products necessarily vary in their composition as a function of the precise conditions used. For a review of *trans* fatty acids, see Dutton (1971). The possible health consequences of feeding *trans* fatty acids to animals and man have also been reviewed (Mensink and Katan, 1990; Emken, 1991). In essence, it appears that *trans* fatty acid-containing diets may modify lipoprotein metabolism similarly to diets that are rich in saturated fatty acids. The extent to which these fatty acids may affect dog and cat metabolism has not been studied to date.

Medium-Chain Triacylglycerols

Medium chain triacylglycerols (MCTs) are those primarily containing a mixture of fatty acids 8:0 and 10:0 with small amounts of 6:0 and 12:0. Hydrogenated coconut oil is a source of MCTs, but it also contains other longer-chain fatty acids and must be fractionated to obtain more pure preparations of MCTs. MCTs are readily hydrolyzed during digestion and reportedly absorbed and transported through mesenteric capillaries into the portal circulation (Bach and Babayan, 1982). Recent data in dogs have provided evidence that short-term feeding of a low-fat diet (5.35 percent fat, as is) containing 3.2 percent 8:0 (as is) and 1.5 percent 10:0 (as is) resulted in some absorption of these MCT fatty acids into the intestinal lymphatics (Newton et al., 2000). Overall, MCTs do not have the same energy value because of their shorter chain length, although their more direct route of absorption may provide other benefits (Remillard and Thatcher, 1989). In spite of this potential benefit, MCTs reportedly decrease food palatability for dogs (Remillard and Thatcher, 1989) and appear to be contraindicated in cats (MacDonald et al., 1985). Indeed, feeding dogs a diet containing 22 percent of dietary metabolizable energy (ME) in the form of MCTs was found to depress food intake along with increased plasma lipid concentrations (Van Dongen et al., 2000). However, when dogs were fed 11 percent of dietary ME as MCTs (total fat 13.4 percent, as is) for 14 days, there was no food refusal, no influence on rate of food ingestion, and no effect on plasma cholesterol and phospholipid concentrations (Beynen et al., 2002). Fat digestibility in these dogs averaged 95.3 percent of intake. Also, no effects on protein digestibility or calcium or magnesium absorption were noted (Beynen et al., 2002). Because these studies were short term, it is unknown whether the amount of MCTs used in the latter study might be of an order of magnitude to define a presumed safe upper limit (SUL) for this nutrient. Small amounts such as those present in hydrogenated coconut oil (i.e., approximately 9 percent and 7 percent of total fat for 8:0 and 10:0, respectively) are unlikely to be detrimental in practical diets containing a total coconut oil content of 10 percent or less (as is).

Conjugated Linoleic Acid

Conjugated linoleic acids (CLAs) are naturally occurring fatty acids found principally in ruminant species. These acids are a mixture of positional and geometric isomers of LA (Δ9,12-18:2n-6). They have one of two double bonds translocated at Δ9 and Δ11 or at Δ10 and Δ12 positions in a chemical structure known as a conjugated diene rather than in a methylene-interrupted sequence as in LA. Because each double bond can be in either the *cis* or the *trans* position, eight geometric isomers of Δ9,11 and Δ10,12 can exist. Other singular positional isomers of CLA include Δ7,9, Δ8,10, Δ11,13, and Δ12,14, and each of these can occur in the following geometric configurations: *cis, trans; trans, cis; cis, cis;* and *trans, trans* (Sehat et al., 1998). However, one primary isomer, c9,t11-18:2 is typically distinguished from the others and has been the subject of numerous investigations. Nonetheless, it should be noted that the term CLA typically refers to mixtures of these isomers, although in many studies the term has been used to describe the group of Δ9,11-18:2 isomeric forms.

As noted above, CLAs are naturally produced in ruminants as normal isomerization products of LA by rumen bacteria. Preferential transformation to the Δ9,11-18:2 isomer group accounts for it being one of the major forms of this fatty acid. Biotransformation of *trans* fatty acids in this way, accounts for small percentages of these fatty acids in ruminant fats and tissues as well. CLAs also can be generated by autooxidation of LA in the presence of hydrogen. Consequently, meat processing procedures including cook-

ing or grilling, especially at high temperatures, may increase CLA content of meat and meat products, although several other factors may affect this conversion (Siems et al., 2001).

Several potentially beneficial effects have been ascribed to CLAs including antiatherogenic properties by using rabbit and hamster model systems (Lee et al., 1994; Nicolosi et al., 1997). However, a study in mice demonstrated that CLAs at 0.5 and 0.25 percent of the total diet increased fatty streak development (Munday et al., 1999). It was initially proposed that CLAs may function as antioxidants, thereby protecting low-density lipoproteins from oxidation. However, an in vitro investigation showed that this did not occur (Van den Bergh et al., 1995). More important to canine and feline species are the potential effects of CLAs on body fat content, skeletal muscle growth, and bone metabolism or as an anticarcinogen; these possibilities await future study. With the exception of a few published abstracts of dog and cat studies (Bartges, 1999; Schoenherr and Jewell, 1999), all data published to date have been obtained using cell cultures or other animal species (Pariza, 1991, 1997; Ip et al., 1994a,b; Haufmann, 1996; Park et al., 1997; Li and Watkins, 1998; Watkins et al., 2000). For a review of CLAs and their health effects, see Watkins and Li (2001) and Haufmann (1996).

Other Sources

Other sources of dietary fats in dog and cat diets that may sometimes be overlooked include eggs, muscle, and offal that comprise many typical ingredients used in pet food manufacture. The overall fatty acid composition of a finished food product ultimately depends on all fatty acids contained in the ingredients. Many of the common ingredients used in dog and cat food manufacturing such as poultry by-product meal and lamb meal, while not primary sources of dietary fat, do contribute a source of dietary fatty acids to a finished product. It is for this reason that fatty acid profiles of some of these commonly used ingredients have been included (see Table 13-2).

As might be expected, these ingredients will vary as to their fat content and fatty acid composition. For example, whole wheat, although low in total fat, may contribute appreciable amounts of LA. Poultry by-product meal and lamb meal also may contribute several PUFAs, but their types may vary depending on diets fed these animals prior to slaughter and regions of origin of food ingredients (Table 13-2).

ANALYTICAL PROCEDURES

Acid Hydrolysis

Food fats are composed principally of triacylglycerols with smaller amounts of more complex lipids. The lipid materials extracted from a food ingredient using anhydrous diethyl ether are termed crude fat and are primarily triacylglycerols with minor amounts of chlorophyll and xanthophylls. Lipids in extruded or baked food products require that the material be acid hydrolyzed prior to ether extraction, otherwise significant underestimation of crude fat will occur (Budde, 1952; Hoffman, 1953). Other solvent systems may also be used and are necessary to ensure extraction of more polar lipids that may be present (see discussion of total lipid extraction below).

Extraction and Saponification of Fatty Acids

Both simple and compound lipids and some non-glycerol-based lipids (i.e., cholesteryl ester and sphingomyelin) contain substantial amounts of individual fatty acids. Specific fatty acid families (n-6 and n-3 series) have become an important feature in canine and feline nutrition and modern petfood manufacture. Thus, when an accurate analysis of the total fatty acid profile of a food or food ingredient is desired, additional techniques are required. A recently peer-verified technique has been published by the American Association of Analytical Chemists International based on determination of total fat in feeds by the Caviezel method (Anonymous, 1997). This method complies with the new definition of fat from the U.S. Food and Drug Administration (FDA). It takes into consideration all fatty acid chain lengths, from C_4 to C_{24}, when fat is present at 0.3-100 percent. Using tridecanoic acid as an internal standard, the sample is added to the solvent *n*-butyl alcohol. The fat is extracted and simultaneously saponified by potassium hydroxide, and the potassium salts are converted to fatty acids by addition of an acidic aqueous salt solution, producing a two-phase system. The upper phase containing the fatty acids and standard is subjected to the fat determination system and subsequent gas chromatographic separation of individual fatty acids. The fat content is determined from fatty acid peak areas and calculated as triacylglycerol.

Extraction for Total Lipid Analysis

An alternative method often used in research laboratories is the extraction of total lipid content using a relatively more polar solvent prior to fatty acid analysis with gas chromatographic techniques. A chloroform-methanol mixed solvent (2/1, v/v) is recommended for the initial extraction. This solvent ensures that all fatty acid-containing lipid components including those belonging to the non-triacylglycerols (e.g., cholesteryl esters, phospholipids, nonesterified fatty acids) are extracted (Folch et al., 1957; Bligh and Dyer, 1959). Addition of 0.2 percent glacial acetic acid to this solvent mixture improves extraction yield as a result of protonation of the polar lipids prior to their partition into the chloroform-methanol (Bauer and Ransone, 1983; Nelson, 1991). Alternate solvent systems also have been proposed using isopropanol-hexane, but

chloroform-methanol remains the solvent of choice for this purpose (Nelson, 1991).

Prior to the advent of gas chromatography, analytic fat constants such as iodine value, saponification value, and melting point were used to characterize fat quality and degree of unsaturation. Although much of these earlier data exist, they are used only in a very general sense in modern laboratory practice for the assessment of fat quality and fat type. However, many laboratories do use some of these techniques. Finally, valid and reliable methods are needed to assess the extent of oxidation of fats and oils. Methods for measuring lipid oxidation and oxidative deterioration in foods have been described along with their advantages and limitations (Warner and Eskin, 1995).

FAT ENERGY AND NUTRIENT DENSITY

Dietary fat provides the most concentrated source of energy in the diet. It accounts for approximately 2.25 times the metabolizable energy (ME) of either protein or carbohydrate. Consequently, alterations in the fat content of a diet can significantly affect its caloric density. Because animals typically eat to meet their energy needs (Cowgill, 1928; see Chapter 3), wide changes in caloric density may require the adjustment of other nutrients such as protein, vitamins, and minerals. Such adjustments are necessary to maintain an appropriate nutrient-energy profile. For example, as caloric density increases, if protein remains constant, then the protein:energy ratio would decrease. Intake of total protein mass then would decrease if the animal stopped eating when its energy needs had been met at each meal. A net decrease of protein intake would thus result over time (Elvehjem and Krehl, 1947; Crampton, 1964).

DIGESTION AND ABSORPTION

Digestion of dietary fat (lipase-mediated hydrolysis) and its absorption is a multistep process requiring intrinsic coordination of three recognized stages in the upper gastrointestinal tract (Maskell and Johnson, 1983)—luminal, mucosal, and secretory (into portal or lymphatic circulation). Each contributes its share to the total digestive environment.

Preduodenal Lipase

The luminal phase begins with preduodenal hydrolysis of ingested fat under the control of lingual and gastric lipases. These enzymes are active at gastric pH and do not require bile salts for activity. The presence of these lipases varies somewhat, depending on animal species. Lipase originating in the oropharyngeal area (lingual lipase) has been described in rat, man, and ruminants (Nelson et al., 1977). However, only traces of lingual lipase activity have been found in adult dogs (Iverson et al., 1991), and no activity has been demonstrated to date in cats (Knospe and Plendl, 1997). It is unknown whether lingual lipase activity might be higher in newborn puppies, but histochemical evidence shows an absence of a lingual lipase in newborn kittens (Knospe and Plendl, 1997). Early reports on the existence of lingual lipases in various species should be interpreted cautiously because sensitive techniques for assay were not available and bacterial contamination of samples was likely in many studies (Douglas et al., 1953).

Both dogs and cats have been found to have gastric lipase activity (Nelson et al., 1977; Hamosh, 1984; Carriere et al., 1992; Descroiz-Vagne et al., 1993; Knospe and Plendl, 1997; Vaganay et al., 1998). Activities in dogs are reportedly highest in the cardia area and greater curvature and lowest in the antrum and lesser curvature of the stomach (Iverson et al., 1991). Histochemical evidence for strong enzymatic lipase activity in the gastric mucosa in suckling kittens, persisting as long as the animals were nursed, also has been demonstrated (Knospe and Plendl, 1997). It should be noted that, in contrast to earlier studies in adult cats, histochemical evidence of gastric lipase in both weaned and adult cats could not be demonstrated in a later study, although it was found in kittens (Knospe and Plendl, 1997).

In dogs and cats, gastric lipase hydrolyzes triacylglycerol to a certain extent in the stomach. As an initial step of dietary fat digestion, the resulting amphipathic lipids formed actually facilitate triacylglycerol emulsification (Hamosh et al., 1975). This observation was confirmed by Linthorst et al. (1977) who showed that the combination of bile salts and lipolytic products (i.e., mono- and diacylglycerols) present in the intestine participated in the emulsification of additional triacylglycerol, requiring only low shear forces for formation. Such pre-hydrolysis of dietary triacylglycerols supports the belief that the diacylglycerols, as well as triacylglycerols, are appropriate physiologic substrates for pancreatic lipase (Verger, 1984). Another study found that the fractional amount of dietary triacylglycerol hydrolyzed in vivo was higher after the ingestion of a preemulsified meal than from a similar quantity of unemulsified fat (Bergstrom et al., 1957). Taken together, more efficient fat digestion occurs because of emulsification of lipids.

Pancreatic Lipase

When free fatty acids leave the stomach, they help stimulate cystokinin release by the duodenal mucosa. Here, mixed micelles are formed by incorporating bile salts and a colipase with the fatty acids and acylglycerols, resulting in the formation of a suitably activated substrate for pancreatic lipase action on triacylglycerols. Cholesterol, cholesteryl esters and other esters (e.g., retinyl esters), and phospholipids all participate in micelle formation. The fatty acyl ester bonds of these molecules also are hydrolyzed to various extents. Triacylglycerols are broken down to free fatty acids and mono- and diacylglycerols.

Other Lipases

Several other lipases are secreted by the pancreas in addition to pancreatic lipase. These include pancreatic colipase and carboxyl ester hydrolase (Borgstrom, 1975; Rudd and Brockburn, 1984; Mickel et al., 1989). Pancreatic colipase exists in multiple forms. The nascent form is a pro-colipase, which is secreted as such in pancreatic juice (Vandermeers et al., 1975). The chemistry and physiology of colipase has been reviewed (Lowe, 2001). After its secretion into the duodenum, pro-colipase is converted into its active form by trypsin (Borgstrom, 1975) via limited proteolysis at both the C- and the N-terminal ends. The resultant active colipase functions principally to restore the activity of bile salt-stimulated pancreatic lipase as the micellar concentration of acylglycerols changes over time. In essence, as the bile salts desorb pancreatic lipase from its interface with its emulsified substrate, colipase functions by anchoring it to the substrate in the presence of the bile salts (Borgstrom, 1975).

The hydrolysis of cholesteryl esters is regulated by an additional lipolytic enzyme, cholesteryl esterase, which was first demonstrated in dog pancreas extracts and pancreatic juice. Data on this enzyme have been reviewed (Rudd and Brockburn, 1984). It has been speculated that the action of this lipase initially depends on pancreatic lipase-mediated hydrolysis of triacylglycerols, whose products establish the appropriate physical environment for subsequent cholesteryl esterase action. As such, conditions become favorable for cholesteryl esterase to hydrolyze cholesteryl esters or retinyl esters. In this way, the overall substrate specificity of the enzyme for several types of dietary esters is extended (Rudd and Brockburn, 1984).

Finally, a phospholipase A_2 also exists that hydrolyzes dietary phospholipid. It is synthesized in an inactive precursor form and secreted into the intestine where limited trypsinolysis occurs, providing the active enzyme and a small activator peptide for phospholipid hydrolysis.

Summary of Triacylglycerol Hydrolysis

The process of lipid digestion is integrated under the action of several lipases. Although the bulk of dietary triacylglycerol is hydrolyzed via pancreatic lipase, this phenomenon is dependent on the action of gastric lipase, colipase, and several other factors as well (Bengtsson-Olivecrona et al., 1994). First, gastric lipase is stable and acts over a wide pH range (Carriere et al., 1991, 1992). It appears to attack virtually any lipid droplet, and its action results in hydrolysis of some triacylglycerol to diacylglycerol and fatty acids. This gastric hydrolysis facilitates emulsification of lipids and prepares them for intestinal digestion. Pancreatic lipase seems to have strict requirements for a physiologic substrate-water interface (i.e., formation of mixed micelles). Bile components help provide a suitable environment for micelle formation and also continue to solubilize the resulting lipophilic products. The rate of bile salt uptake by the jejunum is low compared with that by the ileum. Thus, bile salts remain in the intestinal lumen and can participate in the formation of new micelles until their partial reabsorption in the lower small intestine.

Because long-chain fatty acids and cholesterol are relatively nonpolar, most of the end products of hydrolysis remain in the micelle rather than in solution in the aqueous phase (Hoffmann, 1963). The bile salts themselves are in an equilibrium between the micelle and the surrounding aqueous environment (Carey and Small, 1970, 1972). Bile salts also assist in the desorption of other proteins from the surface of lipid droplets. Pancreatic colipase ensures that pancreatic lipase can become adsorbed to lipid droplets. Carboxyl ester hydrolase, due to its wide substrate specificity, hydrolyzes monoacyglycerols, cholesteryl esters, retinyl esters, and other lipid esters that may be present. Hence, this hydrolase complements the narrow substrate specificity of colipase-dependent pancreatic lipase. An additional point of interest for fat digestion in neonates is that carboxyl ester hydrolase also is secreted by the lactating mammary gland. Because this lipase is active only in the presence of certain bile salts, it is inactive in milk. In the digestive tract, it becomes active only after its arrival in the duodenum.

Absorption

Absorption of the hydrolyzed products of fat digestion occurs in the enterocyte of the small intestine. It is generally assumed that most lipid uptake occurs by passive diffusion. However, some component of it also may be carrier mediated. All biological membranes, including the intestinal enterocyte, possess a layer of relatively unstirred water through which solutes must move by diffusion; this layer is referred to as the unstirred water layer (UWL). The UWL consists of a series of progressively stirred aqueous environments that extend from the intestinal brush border membrane until it blends with the bulk aqueous phase (Thomson and Wild, 2001). The thickness and surface area of the UWL provide characteristic resistance to passive absorption. In the canine jejunum, UWL thickness has been estimated to be from 500 to 1,000 μm (Ryu and Grim, 1982). There is evidence to suggest that the thickness of the UWL may be specific for individual conditions and therefore variable (Thomson et al., 1993). In any case, for absorption of micellarized lipid to occur, lipid products must diffuse across the intestinal UWL where they are protonated prior to traversing the intestinal brush border membrane (Dietschy et al., 1971). This process occurs by either passive diffusion or protein-mediated mechanisms. Protein-mediated movements of lipid across the brush border membranes include lipid-binding proteins for both long- and medium-chain fatty acids as well as for cholesterol (for review, see Thomson and Wild, 2001).

Once inside the cytosol of the enterocyte, fatty acids are bound to fatty acid binding proteins and transported to the

endoplasmic reticulum where reesterification of free fatty acids and reassembly of triacylglycerols occurs (Ockner and Manning, 1974). Similarly, cholesterol is bound and transported by a sterol carrier protein (Scallen et al., 1985). Reesterification of the absorbed fatty acids to monoacyglycerols take place via a triacylglycerol synthase complex and the monoacylglycerol pathway (Brindley, 1974), and cholesterol also may become esterified with a fatty acid by acyl:cholesterol acyl transferase. Such reesterification helps maintain a concentration gradient for additional absorption. Some portion of the fatty acids may pass directly into the portal circulation, with the remainder being formed into lipoproteins in conjunction with cholesterol, phospholipids, and enterocyte-synthesized apoproteins for secretion into the lacteals. Most notable among the enterocyte-synthesized lipoproteins in response to a fat-containing meal are the chylomicra. For a review of lipoprotein metabolism, see Gotto (1986) and Bauer (2000).

DIGESTIBILITY

Apparent digestibilities of crude fat are generally high, although some subtleties do exist depending on fat type and amount and the presence of other dietary components. The apparent digestibility of fat in dogs can vary from approximately 85 to 95 percent when mixed acylglycerols from both plant and animal sources are fed (James and McCay, 1950; Orr, 1965; Meyer, 1984). A recent study found that the apparent fat digestibility of commercially available dry extruded-type diets varied between 70 and 90 percent (Huber et al., 1986). Total fat digestibility was unchanged when texturized vegetable protein from soy was compared with beef in cannulated dogs (Hill et al., 2001). In young dogs (3 to 9.5 months old), the digestibility of beef tallow was dependent on the unsaturated fatty acid concentration of the diet (Meyer et al., 1992). Using diets that were 35 percent dry matter (DM) as fat and with unsaturated acids less than 40 percent of total dietary fat, the digestibility of beef tallow decreased to 81-86 percent. This range of values compared with 95 percent digestibility when more than 50 percent of total fat was present as unsaturated fatty acids.

In cats, reported apparent digestibilities were 99 percent when a diet of beef and mutton was fed (Morris, 1977). In a group of commercial foods, values ranged from 85 to 94 percent (Norvel, 1978). Kane et al. (1981) reported that the apparent digestibility of fat was 90 percent when fed at 10 percent of DM but increased dramatically (97-99 percent) when fed at either 25 or 50 percent dry matter. Peachey et al. (1999) recently compared apparent digestibilities in young versus senior cats when fed beef tallow-, sunflower oil-, and olive oil-enriched diets. They found that young cats (3.0 ± 0.9 year) have somewhat greater apparent total fat digestibilities than do senior cats (11.6 ± 1.4 year) at 94.4 versus 92.2 percent, respectively. Total fat content of the diets used in these studies was approximately 44 percent DM. It also was noted that saturated fatty acids had the lowest apparent digestibility (95.2 percent in young vs. 93.2 percent in senior cats), followed by monounsaturated (98.2 percent vs. 96.4 percent, young vs. senior), and polyunsaturated (98.7 percent vs. 98.0 percent, young vs. senior) fatty acids. Shorter-chain fatty acids were more easily digested than longer-chain types. It seems that a reduction in fat digestibility with age may be a general phenomenon for all fatty acid groups (Peachey et al., 1999). By contrast, Munday and Lowe (1993) found that apparent total fat digestibilities in growing cats progressively increased at 9, 11, 13, 15, and 17 weeks of age, citing the following percentage digestibilities, respectively: 81, 86, 88, 88, and 91 percent.

In other studies using different species, the saturated fatty acid stearic acid also was the least readily digested (Schrijver et al., 1991; Hwang et al., 1994; Mountzouris et al., 1999) and shorter-chain acids appeared to be digested more readily (Cera et al., 1990).

The form of the dietary fat also may alter its apparent digestibility (Adams and Jensen, 1984). In weanling pigs, average fat digestibility of in-seed fat was only 74.9 percent compared to 90.2 percent for the fats extracted from corn, soybean, and sunflower seeds. Similar findings might be anticipated in dogs and cats, although no literature reporting such a distinction is presently available.

The dietary recommendation of fat for domestic cats is currently 9.0 percent on a dry matter basis (about 19 percent of energy) (AAFCO, 2003). However, it appears that felines can tolerate and digest amounts as high as 67 percent ME (MacDonald et al., 1984a), and possibly even higher. Observations of feeding pattern and behavior of large cats also have provided some clues as to the fat content of their diets. It has been estimated that large cats obtain 60 percent of their total calories from dietary fats and that diets up to 67 percent ME as fat are efficiently digested and utilized (Scott, 1968). The apparent digestibility of crude fat by captive wild felids has been reported to be 95-99 percent (ME) when fed a meat-based diet containing 160 g crude fat·kg^{-1} (Barbiers et al., 1982). In addition to the domestic cat, the lion, *Panthera leo*, and cheetah, *Acinonyx jubatus*, also seem to lack the ability to efficiently desaturate fatty acids at the Δ6 position (Davidson et al., 1986; Bauer, 1997). Cheetahs belong to a different genus than do either lions or domestic cats and demonstrate other adaptive differences from these species (Myers, 1974; Kingdon, 1977). The cheetah is diurnal, does not cache its food, and does not scavenge (Myers, 1974). Another difference is that cheetahs are more frequently robbed of their kill; so, they must compensate by being extraordinarily efficient hunters (Kingdon, 1977). In this way, for better or worse, the freshness of their food supply is ensured. From the perspective of dietary fat requirements, the possibility exists that their long-chain polyunsaturated fatty acid (LCPUFA) supply must be oxidatively unspoiled. In one study, the liver fatty acid profiles of two cheetahs killed in the wild versus one captive animal showed markedly

lower amounts of nearly all highly unsaturated long-chain fatty acids in the captive animal tissue (Davidson et al., 1986). The authors noted that this animal had been fed in captivity most of its life and that the possibility of dietary fatty acid deterioration may have been a factor in the differences that were seen.

BIOCHEMICAL BASIS OF FATTY ACID ESSENTIALITY

Biosynthesis

Mammals can synthesize saturated fatty acids de novo starting with glucose, except for some ruminants, or amino acids by the production of a common precursor, acetyl coenzyme A (CoA). The biochemistry of these processes has been reviewed (Salati and Goodridge, 1996). Additional end products are the 16- and 18-carbon monounsaturated fatty acids belonging to the n-7 and n-9 fatty acid families (16:1n-7 and 18:1n-9). These acids are the result of the introduction of a single double bond between carbons 9 and 10 of the respective saturated acids. The enzymes involved in these reactions are active when high-carbohydrate, low-fat diets are consumed but suppressed with high-fat diets. Thus, animals fed relatively high-fat diets will not synthesize their own fatty acids at a high rate. Instead, they utilize the dietary supply of fatty acids, including those of the n-6 and n-3 fatty acids families that are not synthesized de novo.

In contrast to animals, plants can manufacture all of the aforementioned fatty acids plus those belonging to the n-6 and n-3 families. This synthesis of unsaturated fatty acids is accomplished by inserting additional double bonds between the existing n-9 bond and the methyl end of the 18:1n-9 molecule. Enzymes responsible for these reactions include a Δ12 desaturase, producing linoleic acid (18:2n-6), and a Δ15 desaturase, which inserts a double bond into 18:2n-6 to produce α-linolenic acid (18:3n-3) (Cook, 1996). Many marine plants are able to insert additional double bonds into 18:3n-3 with subsequent chain elongation, thereby accounting for the formation of long-chain n-3 polyunsaturated fatty acids (PUFAs) and their abundance in marine oils. However, terrestrial plants do not typically insert additional bonds into 18:2n-6. Thus, arachidonic acid (AA, 20:4n-6) is not found in plant materials.

The inability of animals to synthesize n-6 and n-3 fatty acids via Δ12 and Δ15 desaturases is the cornerstone of fatty acid essentiality. Once n-7 or n-9 fatty acid families are produced or n-6 or n-3 acids are ingested, further metabolic conversions occur in dogs and to a lesser extent in cats. In dogs, rats, mice, and man, these conversions are regulated by a Δ6 desaturase (Cook, 1996; Dunbar and Bauer, 2002; Rodriguez et al., 1999). Cats are unusual among mammals in that they have limited Δ6 desaturase activities (Rivers et al., 1975; Pawlosky et al., 1994). This latter observation further distinguishes the essential fatty acid requirements of cats because, without Δ6 desaturase, conversions of EFAs to other physiologically important PUFAs may not occur. Consequently the long-chain polyunsaturated fatty acid (LCPUFA) products of these conversions also may be essential in the feline species especially under certain physiological conditions. For that matter, there is a growing body of evidence that LCPUFAs may be essential during normal development of dogs and cats as well as several other species that demonstrate insignificant Δ6 desaturase activities compared to adults (Carlson, 1990; Simopoulos, 1991; Conner et al., 1992; Uauy et al., 1996; Pawlowsky et al., 1997; Waldron et al., 1998).

Desaturation and Elongation

As noted, mammals can introduce a double bond between the 9- and 10-position of de novo-synthesized saturated acids. In the absence of any dietary n-6 or n-3 PUFA, these resultant monounsaturated fatty acids (i.e., 16:1n-7 and 18:1n-9) can serve as substrates for Δ6 desaturase. Oleic acid (18:1n-9) thus can be converted into 18:2n-9, 20:2n-9, and 20:3n9 (Figure 5-2). (Interested readers should refer to Voss et al., 1991, for details of the peroxisomal pathways for 22-carbon PUFA synthesis.) The fatty acid, 20:3n-9 is also known as Mead acid, and its accumulation is a hallmark of EFA deficiency (Holman, 1960).

When EFAs are present, the Δ6 desaturase reaction is the rate limiting step in a cascade of desaturations and elongations of n-6 and n-3 fatty acids that also include chain elongations and Δ5 desaturation (Cook, 1996). The net result is the production of a variety of LCPUFAs including arachidonic (AA, 20:4n-6), eicosapentaenoic (EPA, 20:5n-3), docosapentaenoic (DPA, 22:5n-3), and docosahexaenoic (DHA, 22:6n-3) acids. Specific amounts of these LCPUFAs depend on competitive interactions among the various substrates and their products and the specific cell type involved (Smith, 1992). It is noteworthy that as a result of animals' lost capacity to insert double bonds in position 12 and 15, interconversions of the n-3, n-6, n-7, and n-9 families cannot occur. The argument for fatty acid essentiality is again apparent because the n-6 and n-3 fatty acids are needed for important physiologic functions.

Fatty Acid Ratios

Numerous reports from professional and government committees have advocated modifications of the intake of various n-6 and n-3 PUFAs over the past 20 years. In some instances, dietary recommendations have included specifying n-6 to n-3 acid ratios. To help clarify this concept, it should be noted that different methods of calculating this ratio have been employed. Not all of the resultant ratios reflect dietary fatty acid profiles that are metabolically equivalent. For example, some studies defined the ratio as the sum of *all* n-6 PUFAs to *all* n-3 PUFAs (total n-6 to total n-3 ratio; including all derived LCPUFAs), whereas in other

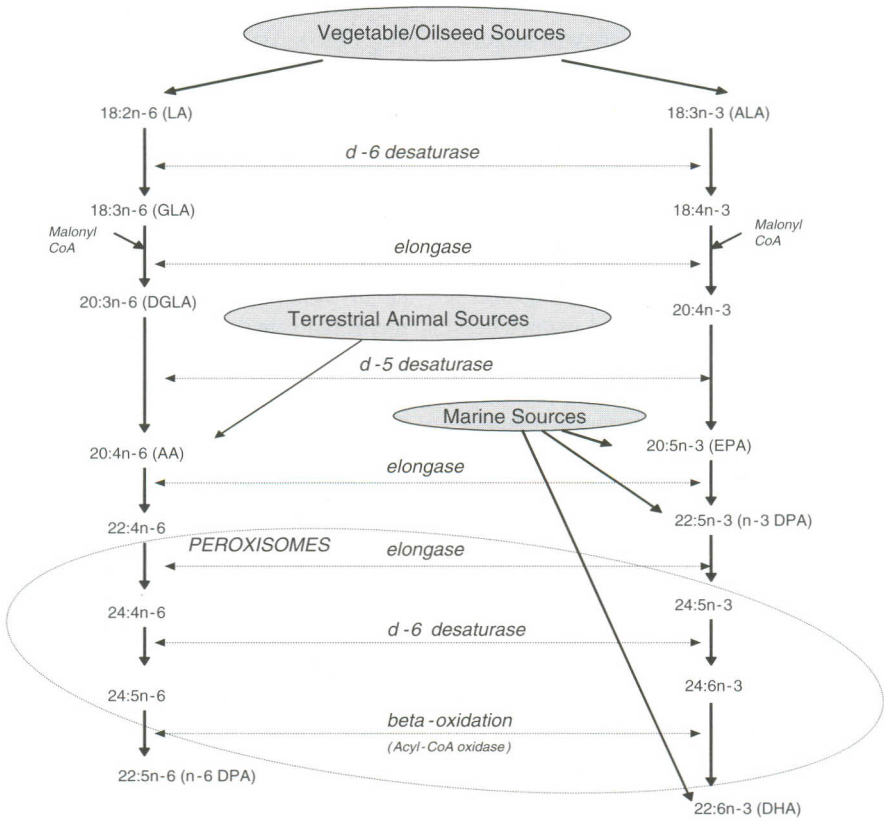

FIGURE 5-2 Predominant pathways of essential fatty acid metabolism in mammals. Enzyme abbreviations: d-6 desaturase = Δ6 desaturase; d-5 desaturase = Δ5 desaturase; elongase = chain elongase.

cases the value is calculated using only the 18-carbon parent fatty acids (LA and ALA). A further complication arises in that review articles on the topic often do not clearly specify this difference. Most studies have typically used long-chain n-3 PUFAs (marine sources), but vegetable sources (18-carbon n-3 acids) also have been employed, and some studies reported using mixtures of both vegetable and marine sources. This latter practice is complicated when a single ratio is calculated because the long-chain metabolites are known to be more potent as substrates for eicosanoid production than their parent fatty acids. For example, greater amounts of 18:3n-3 must be fed at constant 18:2n-6 to achieve a similar eicosanoid effect to that obtained by using a lesser amount of 20:5n-3 (Anonymous, 1992b). Furthermore ALA and marine n-3 LCPUFAs have distinct physiologic effects on plasma and tissue enrichment in their own right. Such metabolic differences have been observed in dogs (Vaughn et al., 1994; Waldron 1999; Rees et al., 2001).

An important recent development in the use of fatty acid ratios has been agreement by participants at two expert workshops convened in Europe and the United States in recommending dietary n-3 fatty acids to help decrease risk of coronary artery disease. Both groups, and others, agree that the four types of PUFA—18:2n-6, 18:3n-3, n-6 LCPUFAs (primarily 20:4n-6), and n-3 LCPUFAs (primarily 20:5n-3 and 22:6n-3)—should be considered separately when making dietary recommendations (Anonymous, 1992b; de Deckere et al., 1998; Buttriss, 1999; Simopoulos et al., 1999).

The European expert committee also specifically concluded that the use of a total n-6:n-3 ratio is not helpful (de Deckere et al., 1998). The British Nutrition Foundation Task Force on Fatty Acids (BNF) has stated that attempts to explain data based on the total n-6:n-3 ratio may be distorted (Anonymous, 1992b). Use of the simpler ratio of LA to ALA has been recommended by the BNF until more is known about the relative potencies of various n-3 acid types. The simpler ratio could be used but it does not take into account the extent to which marine-based n-3 PUFAs are also present, which can lead to important metabolic consequences. Additional complexities exist even when this 18-carbon ratio is employed. For example, decreasing the amount of LA in the diet or increasing the amount of ALA may result in the same ratio even though these separate modifications do not have the same metabolic consequences (Anonymous, 1992b). Because the metabolisms of LA and

ALA are not independent of one another (Mantzioris et al., 1995; de Deckere et al., 1998), high cellular LA will affect ALA conversion to a greater extent than high ALA at lower LA content (Dunbar and Bauer, 2001). Thus, where fatty acid ratios are noted in the present recommendations, the method of calculation is indicated.

Essential Fatty Acid Utilization for Structure and Function

The EFAs or their derivatives are those that are required for normal growth and physiologic integrity and cannot be synthesized adequately by the body. All of the lesser unsaturated members of the n-6 fatty acid family (18:2n-6, 18:3n-6, 20:3n-6) have EFA activity by virtue of their conversion to 20:4n-6 and interdependent effects on fatty acid metabolism overall. Because all but the parent fatty acid, linoleic, can be synthesized in dogs, only this fatty acid is regarded as a dietary essential n-6 fatty acid. The α-linolenic acid, n-3, family has historically been regarded as not quite the nutritional equivalent of the n-6 family. Signs of ALA deficiency may be more subtle than LA deficiency (Holman et al., 1982). However, evidence from numerous laboratories has now established ALA (18:3n-3) as a true EFA (Anonymous, 1992a). Although ALA has less potency as an EFA than does LA, several of its long-chain derivatives such as EPA and DHA have important metabolic consequences particularly in nervous tissue and in the inflammatory and immune responses (Carlson, 1990; Conner et al., 1992; Uauy et al., 1996; Simopoulos, 1999). So, in addition to the 18-carbon PUFAs, long-chain derivatives of both the n-6 and the n-3 families may now be regarded as "conditionally essential" especially because of their role in the normal development of premature human infants and possible role in neurological tissue.

COMPARATIVE STUDIES

This section describes the physiologic role of EFAs in health maintenance. Species-specific supportive data on fatty acid essentiality and well-being in dogs and cats are covered later in the appropriate sections. Therapeutic effects of EFAs on disease per se are not covered, although such studies in dogs and cats, both clinical and experimental, have been reviewed (Case et al., 2000; Hand et al., 2000).

Membrane Composition and Integrity

Structurally, the PUFAs are important for maintaining membrane fluidity and related cell functions such as transport, metabolic regulation, and the epidermal water barrier (Prottey, 1977; Elias et al., 1980; Wertz and Downing, 1982). Cell membrane stability, structure, and function are critically dependent on having unsaturated fatty acids incorporated into them. The PUFAs found in membrane phospholipids also affects their shape and ability to pack together (e.g., the normal biconcave shape of red blood cells) (Jos et al., 1985). Tissues that perform such functions as storage (adipose tissue), metabolism (liver), mechanical work (muscle), and excretion (kidney) tend to have cell membranes in which n-6 fatty acids predominate (Gurr and Harwood, 1991a). Other specialized tissues contain unique fatty acids such as n-6 and n-3 LCPUFAs with five and six double bonds but with a higher proportion of the n-3 types. These include reproductive tissue as well as neurologic tissue such as myelin, which is an ion-impermeable insulating cell membrane, and the outer segment cell membranes of rod cells of the eye with their high long-chain fatty acids including high DHA (22:6n-3) (Tinoco, 1982; Gurr and Harwood, 1991a).

Lipid-Protein Interactions

Interactive roles of fatty acids and lipids in membranes with proteins also exist that facilitate conformational changes necessary for membrane protein function. Such interactions are well reflected in the many examples of activities of purified and partially purified membrane proteins being influenced by their lipid environment. Transporter proteins, enzymes, and cell signals, including the inositol-lipid cycle and its second messengers, are examples of these types of interactions (Carruthers and Melchior, 1986; Manzoli et al., 1988; Kinsella, 1990; Anonymous, 1992a).

Eicosanoid Production

Additional functional aspects of the EFAs are that they are precursors of eicosanoids, which includes a diverse group of physiologically active, but often short-lived, fatty acyl-derived metabolites such as prostaglandins, prostacyclin, thromboxanes, lipoxins, leukotrienes, and related hydroxyl fatty acids. These metabolites contain 20 carbon atoms. They are synthesized locally, on demand, by individual cell types in response to their immediate environment. Both cyclooxygenase (CO) and lipoxygenase (LO) are involved in their synthesis, which leads either to prostaglandin or thromboxane from CO-regulated pathways and to leukotrienes from LO reactions (Figure 5-3). Prostaglandins are typically vasodilators, whereas leukotrienes are vasoconstrictors. Leukotrienes also can stimulate neutrophil chemotaxis and thromoboxane release. Additional pathways that have been rarely studied in companion animals are those that result in the formation of epoxy and hydroxy metabolites of 18- and 20-carbon fatty acids, which also have been shown to play a role in modulating cellular responses (Kietzmann, 1990).

Different cell types will produce a variable array of eicosanoids depending on the functional characteristics of the specific cell type involved. Summaries of these effects have been published (Gurr and Harwood, 1991b; Smith and Fitzpatrick, 1996). For example, platelets, when stimulated,

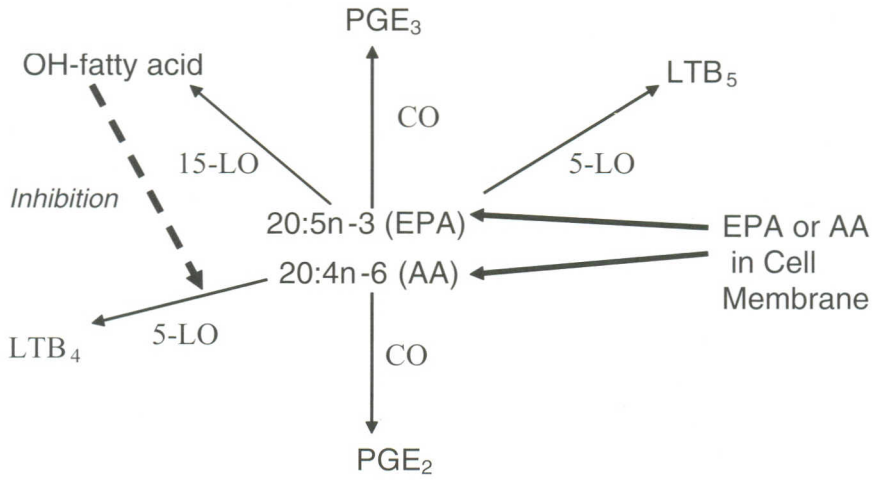

FIGURE 5-3 Generalized pathways of eicosanoid formation from n-3 and n-6 PUFAs. Eicosapentaenoic and arachidonic acids compete with one another for incorporation into cell membranes and as substrates for cyclooxygenase and 5-lipoxygenase. EPA is the precursor of the less active leukotriene B_5 (LTB_5) and can form hydroxyl fatty acids via 15-lipoxygenase, which is a potent inhibitor of leukotriene B_4 (LTB_4).

will synthesize thromboxane A_2, which promotes vasconstriction and aggregation. Leukotriene B_4 (LTB_4) is produced when neutrophils are stimulated as part of the inflammatory response. Also, the same eicosanoids may have opposite effects when produced in different tissues. For example prostaglandin E_2 (PGE_2) is considered proinflammatory in skin because of its vascular dilation effect, whereas it is protective of gastric mucosa in the gastrointestinal tract (Hammarstrom et al., 1975; Miller and Jacobson, 1979). PGE_2 also is involved in helping maintain normal glomerular filtration of kidney because of its vasodilatory effect on renal mesangium (Scharschmidt, 1983).

A necessary prerequisite for eicosanoid production is the availability of an appropriate unesterified fatty acid (Weiss, 1989; Smith, 1994; Bates, 1995; Nelson et al., 1997). In mammals, this is usually AA, which is derived from LA. Thus, although LA and ALA are typically regarded as EFAs, the metabolic significance of AA must be borne in mind. As a fundamental component of cell membranes, AA generally comprises 20-25 percent of the total fatty acids of cell membrane phospholipids of skin and other tissues. Studies with guinea pigs, rats, and humans have found that epidermal microsomes from these species are unable to synthesize AA because of lack of the necessary enzyme systems in skin tissues for conversion from LA. It is generally accepted that in mammals AA is synthesized primarily in liver and then transported to various tissues via circulating lipoproteins. These phenomena have not been confirmed in dogs and cats, but most workers have assumed that the ability of canine skin to manufacture AA is limited.

Thus, where skin health is concerned, the release of AA from tissue cells (e.g., keratinocytes, neutrophils, platelets, macrophages, vascular endothelia, mast cells, fibroblasts) is a rate-limiting step in eicosanoid biosynthesis and subsequent physiologic response (Galli, 1981; Rouzer et al., 1982; Samuelsson, 1983; Terano et al., 1986; Ziboh et al., 1986). The availability of AA in membranes of these cells is central to this cascade of steps, which can alter physiologic responses and, ultimately, animal well-being. The analogous n-3 PUFA, EPA, can competitively substitute for AA, thereby modulating the family of eicosanoids produced and their overall responses. Although these processes are highly cell specific and fundamental to cell membranes, the direct link among eicosanoids, the dietary EFAs, and their derivatives provides a metabolic environment that is particularly responsive to dietary modification. The proportions of tissue n-6 LCPUFAs to n-3 LCPUFAs can be modified by inclusion of dietary n-3 fatty acids and, as noted earlier, the n-3 LCPUFAs are especially effective in this regard compared to 18-carbon n-3 acids. These relationships are competitive and have been determined in rats, humans, and dogs to be hyperbolic and not linear (Lands, 1992; Bauer et al., 2002). This fact must be borne in mind when eicosanoid responses are targeted by way of dietary modification. Also, modifying the amounts of n-6 LCPUFAs should be beneficial because excessive activity of n-6 eicosanoids produced in the body occurs in several health disorders.

Growth and Development

Mammalian species vary in the extent of their retinal and other development in that growth can be classified as prenatal, perinatal, or postnatal with respect to any major retinal growth spurt. Altricial species such as dogs, cats, and rats

generally have the greater part of their retinal development occurring after birth (Dobbing and Sands, 1970), whereas guinea pigs, primates, and humans have both pre- and postnatal development (Dobbing and Sands, 1970; Huang et al., 1990). Compared to humans, rodents and carnivores are born much earlier in their developmental life (Widdowson, 1970). Brain development likely follows this same pattern. Thus, significant brain growth occurs and may even peak during the early neonatal period in rodent and canine animal species. Because myelination follows the peak rate of cell division, major demands are placed on the provision of large amounts of LCPUFAs to support neural development during this time. Thus, in dogs and cats, early lipid nutrition such as that provided by milk fatty acid composition may be significant in understanding developmental needs in these species.

Brain and retinal development in animals and humans depends upon the PUFAs AA and DHA in prenatal and neonatal life (Conner et al., 1992). Primates (Neuringer et al., 1986), rats (Benolken, 1973), and guinea pigs (Weisinger et al., 1996) fed diets deficient in ALA were observed to have large decreases in brain and retinal DHA associated with impaired visual function. Retinal accretion of DHA is significant in development given its high concentration in rod outer segment cells in many animals including dogs (Abedin et al., 1999; Delton-Vanderbroucke et al., 1998). Substantial brain fatty acid accretion occurs during late gestation and neonatal period in rats and is marked by a pronounced accumulation of DHA. In humans during the third trimester of pregnancy, the concentration of DHA increases substantially and continues to be deposited during the first 2 years of life. Accumulation of DHA also has been observed in other species such as piglets, kittens, and nonhuman primates. In retina, DHA may make up as much as 50 percent of the fatty acids. It is found in photoreceptor outer segment membranes of retina, and this tissue tenaciously conserves this fatty acid during periods of n-3 deficiency. Other data suggest that DHA is necessary for improving learning ability in rats (Yamamoto et al., 1987). In rats and humans, the fatty acid composition of cerebral cortical gray matter was most affected by diet during the suckling period (Kanazawa et al., 1995). These observations suggest that reduced amounts of DHA during gestation and lactation may result in suboptimal neural development and therefore underscore the importance of ensuring appropriate maternal EFA, and possibly LCPUFA, tissue status during gestation and the suckling period.

Along with DHA, there is also a need for AA (Carlson et al., 1992; Crawford, 1993). Both DHA and AA are required for vascular development and regulation of blood flow (Fleischauer et al., 1993; Pritchard et al., 1995; Pfister et al., 1996). In premature human infants, amounts of both AA and DHA fell while LA rose in plasma phospholipids during postnatal development (Uauy et al., 1989; Carlson et al., 1996). Thus, dietary strategies to ensure the availability of these PUFAs are needed. Human studies have shown that increasing ALA in an infant formula significantly increased DHA in erythrocytes; yet, it remained below the amount seen in breast-fed infants (Clark et al., 1992; Jensen et al., 1996). Dietary ALA also causes a reduction in plasma AA content, which may be undesirable for neonates (Clark et al., 1992; Jensen et al., 1996). A study was conducted in guinea pigs using either DHA supplementation alone or DHA in conjunction with AA, and these treatments were compared with ALA supplements at constant dietary LA (Abedin et al., 1999). It was found that dietary ALA alone or combined with a DHA + AA supplement increased neural DHA content without affecting AA. However, the LCPUFA supplement also caused enrichment in liver and heart tissues. This study also found that a diet containing 0.6 percent DHA and 1 percent ALA gave the same retinal and brain phospholipid DHA values as one containing 7.1 percent ALA. Thus, dietary DHA is a much more effective direct precursor of tissue DHA than is ALA. This effect is the result of low conversion rates of ALA to longer-chain derivatives (Sinclair, 1975). No alteration of retinal phospholipid AA was seen when the DHA and DHA + AA diets were fed, which is consistent with results found in piglets (Craig-Schmidt et al., 1996).

CANINE STUDIES

Signs of Deficiency or Excess

Low amounts of dietary fat will lead to deficiencies of EFAs and energy. Because of the effect of fat on palatability, ultralow-fat diets may result in decreased intakes, further exacerbating compromised nutritional status. The skin is an important target for EFA deficiency signs because it is one of the largest organs in the body and because of the important role of LA in the transepidermal water barrier. Puppies fed an ultralow-fat diet (estimated at 0.01 percent ME) were observed to have coarse, dry hair with desquamation of skin ventrally after about 2 months, with lesions becoming more severe at 4-5 months. When energy intakes were normal, the onset of these signs was delayed approximately 1 month (Wiese et al., 1962). Gross lesions first appeared on the abdomen, then the thigh, and finally the interscapular regions. With time, the skin became greasy, pruritic, and potentially susceptible to infection because of the altered surface lipids, bacterial flora, and presence of secondary bacterial invasion to varying extents (Codner and Thatcher, 1990). Histologically, the epidermis became thickened and edematous, with numerous cell layers building up in the most affected regions. Keratinization of the skin with parakeratosis occurring in more advanced stages also developed. Impairment of epithelial cells with invasion of monocytes and neutrophils leading to ulceration also was noted. These clinical signs resolved after administration of diets providing 2 percent or more of total calories as LA (Hansen et al., 1954; Weise et al., 1966). Substituting ALA did not appear to completely resolve these problems.

In addition to skin lesions, experimentally produced EFA deficiency in growing rats (Burr and Burr, 1929, 1930), dogs (Hansen et al., 1948, 1954; Hansen and Weise, 1951; Weise et al., 1965, 1966), and cats (MacDonald et al., 1983a) caused renal and reproductive abnormalities, decreased growth rate, immunologic abnormalities, hypotrichosis, alopecia, scaling skin, weak cutaneous blood vessels and an increased tendency to bruise, decreased wound healing, sebaceous gland hypertrophy, and increased epidermal water loss (reviewed by White, 1995). Degenerative changes in numerous other organs and increased cell membrane fragility also have been found (Holman, 1971).

Regarding ALA, Capuchin monkeys maintained on a diet containing adequate LA but little ALA showed signs closely resembling those of LA deficiency that resolved after addition of linseed oil to the diet (Fiennes, 1973).

Clinical manifestations of n-3 fatty acid deficiency because of inadequate intake of ALA are more subtle (Tinoco, 1982). They include nervous system abnormalities such as decreased visual acuity, electroretinographic abnormalities, polyneuropathy, and reduced learning ability (Tinoco, 1979; Holman et al., 1982; Neuringer et al., 1988; Conner et al., 1992; Uuay et al., 1996). Such signs require more technical sophistication to detect clinically. Nonetheless, the brain and retinal rod cells of most species, including dogs, are characterized by a high proportion of long-chain fatty acid derivatives of ALA such as DHA (Anderson et al., 1992; Alvarez et al., 1994; Delton-Vanderbroucke, 1998). A requirement for ALA to support normal growth in rat pups and the need for long-chain n-3 PUFAs such as DHA for cognitive and visual development have often been demonstrated (Pudelkewicz et al., 1968; Anonymous 1992b) and dogs would not be expected to be an exception. By inference then, because these acids cannot be synthesized in the body, a dietary requirement for them is expected. This requirement may be small and may be limited to early development. Counter to this argument, no apparent developmental problems have yet to be reported in dogs because of an ALA or other n-3 PUFA deficiency. However, it is only in recent years that interest in this topic has developed and that analysis of canine diets for the presence of n-3 fatty acids has been conducted.

Overt signs of excessive intake in healthy dogs also remain uncharacterized, although many studies have associated chronic inflammatory conditions with n-6 PUFA excess or n-3 PUFA depletion. There is growing support for the concept that diets generally have become too highly enriched in n-6 PUFAs. The inclusion of additional n-3 PUFAs to blunt the availability of AA may be desirable (reviewed in Lands, 1986). In spite of this, Lands et al. (1990, 1992) have demonstrated that tissue saturation with AA derived from LA using rat and human data appears to occur at a concentration of dietary LA not much higher than its minimum requirement (MR). This phenomenon also appears to be the case in dogs (Bauer et al., 2002). Indeed, one study in dogs found that diets containing 2.5 percent ME LA vs. 27.4 percent ME LA (40 percent of energy total fat) resulted in the same degree of AA enrichment of isolated neutrophils (Waldron, 1999). Thus, simply using tissue saturation of n-6 LCPUFAs as an index of excessive intake is not sufficient to address this question and additional biochemical, functional, or clinical measures are needed. With respect to the n-3 LCPUFAs, deleterious effects on increased bleeding times and platelet function in dogs fed excess amounts of these fatty acids have not been demonstrated, although exhaustive studies relating to dosages have not been performed (Boudreaux et al., 1997).

Early studies on dietary EFAs in dogs focused on the need for n-6 fatty acids for growth and prevention of skin lesions (Hansen et al., 1948, 1954; Hansen and Wiese, 1951; Wiese et al., 1962, 1965, 1966). More recent studies on the interdependence of the n-6 and n-3 EFAs for their metabolism to active long-chain metabolites have added new complexities to the question of essentiality. For example, diets high in ALA (18:3n-3) suppress the conversion of LA to AA (Mohrauer and Holman, 1963; Holman and Mohrauer, 1963; Hwang and Carroll, 1980; Bauer et al., 1998). The competition between these molecules affects both cell structure and function and is the result not only of accumulation of parent compounds but also of their metabolic derivatives and eicosanoids. One important question is to what extent the presence of one fatty acid family will affect the requirement for the other. Data are presently unavailable to answer this question fully. However, studies investigating the effect of PUFA types and amounts on specific responses in dogs have provided some insight. Amounts of recommended minima and maxima ultimately depend on the clinical, biochemical, and physiologic criteria used to define them. Studies in which interactions between n-3 and n-6 PUFAs in canine species have been found are summarized below.

Skin and Hair Coat

The epidermal water barrier function of skin depends on the 18:2n-6 content of the cellular phospholipid fraction known as ceramides. In normal healthy skin, ceramides containing 18:2n-6 are extruded as intercellular lamellar granules from epidermal keratinocytes at the stratum granulosum-stratum corneum interface. This 18-carbon acid enhances cohesion between the lipid sheets that make up these intercellular lamellae, thereby imparting an effective water barrier to the epidermis (Elias, 1987; Freinkel, 1987). This function may explain why many instances of dry, dull hair coat and scaling, nonpruritic skin disorders of dogs generally respond to increased dietary fat in the diet usually provided by vegetable oils. Studies in dogs have shown that both serum and cutaneous fatty acid composition can be modified (Campbell and Dorn, 1992, Vaughn et al., 1994; Campbell and Roudebush, 1995) by dietary supplementation. One study evaluated four diets for 56 days, one of which contained 18:3n-3, and found both serum and cutaneous samples

to be relatively enriched in this fatty acid, a nonsignificant increased sheen of the dogs' hair coats, and significantly lower transepidermal water losses compared to that for the other diets (Campbell and Roudebush, 1995). Unfortunately, the complete lipid profiles of diets used in this study were not reported; so, a thorough comparison of the diets was not performed. More recently, significant short-term improvements in skin and hair coat scores of clinically normal dogs have been demonstrated using ground oilseed supplements enriched in either LA or LA plus ALA (Rees et al., 2001). In this study, 3 percent (w/w) supplementation of diets with either whole ground sunflower seed (9.3 percent ME LA, 0.4 percent ME ALA) or whole ground flaxseed (7.3 percent ME LA, 2.5 percent ME ALA) led to an increase in the amount of circulating n-6 fatty acid. This enrichment likely resulted in the incorporation of LA into lipid ceramide fractions of the epidermis, thereby supporting more desirable skin and coat condition scores. It should be noted, however, that these improvements were only seen with 28 days of feeding and that some adaptation beyond this time occurred (Rees et al., 2001). Also, it could not be determined whether the improvement seen under these conditions was the result of an overall increase in dietary total fat independent of fat type. Another study supplemented an existing diet with LA, zinc, or a combination of LA and zinc and assessed skin and coat quality in dogs (Marsh et al., 2000). The total LA and zinc contents ingested were 12.75 percent ME (ca. 15 g per 1,000 kcal) LA and 100 mg zinc per 1,000 kcal. Dogs supplemented with the combination of nutrients showed significant improvement in coat gloss and significant decrease in transepidermal water loss over the 9-week test period. These amounts are substantially greater than the amounts recommended to prevent deficiencies of these nutrients. The possibility of a total fat effect could once again not be ruled out from these data.

Inflammatory and Immune Cell Structure and Function

Nutritional modification to decrease the amount of AA available for eicosanoid synthesis and provide alternative substrates for the enzymes LO and CO is believed to lessen the inflammatory response. Recommendations for health maintenance have been based on the potential benefits of decreasing known mediators of inflammation especially because of their possible involvement in chronic, progressive diseases such as osteoarthritis and those of the gastrointestinal tract, kidney, and skin. Both n-6 and n-3 fatty acid families appear to participate in these effects but generally by different mechanisms.

n-6 Fatty Acid Effects

The antiinflammatory effect of n-6 fatty acids relates to the synthesis of dihomogammalinolenic acid (20:3n-6, DGLA) from dietary γ-linolenic acid (18:3n-6) (Miller and Ziboh, 1988). Although these intermediates can be further converted into AA, such conversions occur more slowly when GLA is fed in supplemental or higher amounts. Under this condition, accumulation of DGLA and competition for inclusion into cell membranes result. Because DGLA is a substrate for LO and CO, it may be converted to the less inflammatory PGE_1 and inhibit the release of AA from other membranes. It also can be converted into a fairly potent antiinflammatory hydroxy fatty acid by virtue of being able to block the LO pathway and additional leukotriene (LTB_4) biosynthesis (Hammarstrom et al., 1979; Miller and Ziboh, 1988). Although concentrations of plasma GLA and DGLA are responsive to diet change, conflicting results have been found in studies with dogs and cats on the utility of using oil supplements containing GLA and other n-6 and n-3 PUFAs in clinical settings (reviewed in Case et al., 2000). Whether cats differ from dogs in their metabolism of GLA because of low Δ6 desaturase is unknown.

n-3 Fatty Acid Effects

Long-chain n-3 PUFAs from fish oil or other marine sources seem to be especially capable of modifying inflammatory and immune responses. Diets containing only ALA as an n-3 source or mixtures of ALA and fish oil may not perform as effectively in this regard when included on an equivalent weight basis (Vaughn et al., 1994; Wander et al., 1997; Waldron, 1999). One reason for this is the inefficient rate of conversion of ALA to EPA (Sinclair, 1975).

Studies in dogs have investigated neutrophil structure and function by using diets supplemented with 18:3n-3 fatty acids from linseed oil, 18:2n-6 from safflower oil, low PUFAs from beef tallow, and fish oil PUFAs for 28 days (18 percent w/w fat supplement added to a basal diet replete in LA) (Waldron, 1999). The fish oil group showed significant enrichment of EPA and DPA over AA, increased neutrophil membrane fluidity and ex vivo phagocytosis, lower LTB_4 production, and decreased superoxide dismutase activities (Waldron, 1999). The n-3 PUFA diets in these studies contained 103 g ALA per kilogram (19.6 percent ME) in the linseed oil group and 45.5 g (EPA + DPA + DHA) per kilogram (8.6 percent ME) in the fish oil group. The fluidity effect may depend on double-bond number up to some maximum because other studies have found that enrichment of cell membranes with DHA actually results in a leveling off of membrane fluidity (Dratz and Deese, 1986; Stubbs and Smith, 1990). Another study described similar blunting of ex vivo neutrophil LTB_4 production when dogs were fed a high n-3 PUFA diet using marine sources compared with corn oil (milligram per kilogram diet amounts of the n-3 PUFA not specified) (Byrne et al., 2000). These findings are consistent with earlier reports that diets containing high marine source n-3 PUFAs were particularly adept at modifying neutrophil and inflammatory skin responses of healthy dogs (Vaughn et al., 1994). This latter study concluded that the ef-

fects seen were because of the ratio of total n-6 PUFAs to total n-3 PUFAs. However, no accounting was given for the varying amounts of ALA in the diets, which have an impact on the calculated ratio, but are less potent overall in blunting biochemical indices of inflammation.

Regarding dietary maxima, one study described older beagle dogs (9.5-11.5 years) being fed one of three diets containing the following: EPA + DPA + DHA, <0.3, 2.2, and 6.15 $g \cdot kg^{-1}$; LA, 24.1, 17.1, and 10.35 $g \cdot kg^{-1}$; and nearly constant ALA, 0.7, 0.7, and 0.85 $g \cdot kg^{-1}$ diet, respectively. After 8-12 weeks, cell-mediated immunity was significantly lower in the 6.15-g (EPA + DPA + DHA) group. Also, PGE_2 response was blunted in mononuclear cells, vitamin E was decreased, and indices of lipid peroxidation were increased (Wander et al., 1997). Percentages of fatty acids on an energy basis in the diet containing the highest n-3 PUFA were calculated as approximately 2.6 percent ME (EPA + DPA + DHA), 4.4 percent ME LA, with a total fat content of approximately 43 percent ME (calculated from Wander et al., 1997). Further, a report by Hall et al. (1999) from this same study also found the highest n-3 LCPUFA diets to have significant effects on CD4+ lymphocytes after vaccination. An additional study fed three amounts of α-tocopheryl acetate in diets with approximately 2.1 percent ME EPA + DPA + DHA (from menhaden fish oil) using a complete diet. The diets contained approximately 6.5 percent ME LA and total fat of approximately 40.4 percent ME (calculated from Hall et al., 2002). Inconsistent effects on plasma α-tocopherol status were found depending on how the data were expressed. Adverse effects were not documented in this study. Plasma cholesterol concentrations were lower in the high n-3 groups, but no triacylglycerol lowering effect was observed.

Based on the few studies in which dietary concentrations can be calculated, it is difficult to state a maximal safe amount of diet n-3 PUFA from marine sources with a high degree of certainty. Most studies have been of short duration, so the question of long-term effects cannot be resolved completely. However, several studies have been conducted in which results allow some conclusions to be reached. One such study found no clinically significant changes in platelet function and coagulation assays when diets containing menhaden fish oil with ratio of a total n-6 to total n-3 of 5:1 was fed (Boudreaux et al., 1997). Mooney et al. (1998), when feeding this same diet, found biochemical evidence that n-3 fatty acids affect the inflammatory stage of wound healing but selected quantitative histological factors were unaffected. Also, Scardino et al. (1999) compared fish versus soybean oil-supplemented diets containing total n-6:total n-3 of 0.3:1 and 7.7:1, respectively, and reported no statistical evidence that n-3 fatty acids suppress the inflammatory stage of wound healing histologically. However, significantly less epithelialization of open wounds and less wound contraction were found. These findings may lead to more granulation and, possibly, scar formation. In each of these studies, absolute amounts of individual n-3 or n-6 fatty acids or total fat contents of diets used were not described in detail. In the absence of such details, it is not possible to determine at what concentration n-3 LCPUFAs may have adverse effects on canine species. The data of Wander et al. (1997) and Hall et al. (1999) have provided the best dietary concentrations to date showing metabolic alterations that, under some conditions, might be considered a safety risk.

FELINE STUDIES

Signs of Deficiency or Excess

Attempts at devising semipurified diets containing vegetable oils that cats would eat led Rivers and coworkers to a series of experiments on feline essential fatty acid metabolism. In the early 1970s, they observed that domestic cats appeared to require a dietary source of LCPUFAs. Biochemical evidence of this was published in 1975 when cat liver preparations were observed to lack the Δ6 desaturase needed to synthesize AA from LA and EPA from ALA (Rivers et al., 1975). Cats in this study had dry, lusterless hair coats, dandruff, behavioral infertility, and hepatic lipid infiltration. A series of studies published by Rivers and colleagues followed (Hassam et al., 1971; Rivers et al., 1976a,b; Frankel and Rivers, 1978, 1980, 1981; Rivers, 1982) that demonstrated an EFA requirement for cats, a deficiency of which could be caused by feeding hydrogenated coconut oil as the sole fat source. In addition, cats with EFA deficiencies had lower feed efficiency without changing body weight gain, mild mineralization of kidneys (MacDonald et al., 1984a), and changes in platelet aggregation (MacDonald et al., 1984b). Enlarged, fatty livers and histologic fatty infiltration of kidneys also were found.

What made these studies unique, in contrast to those of other mammals, was that EFA deficiency signs were observed even though cats were fed diets containing the requisite LA and ALA (MacDonald et al., 1984a,c). Thus, the possibility of a dietary requirement for LCPUFAs derived from these 18-carbon precursors emerged.

The diets used in the earliest EFA studies in cats may have been marginal in taurine (Hayes et al., 1975; MacDonald et al., 1984a) and vitamin E (Stephan and Hayes, 1978) and had excessive vitamin D content (MacDonald et al., 1984a). However, it was later found that taurine supplementation did not change the fatty acid profiles seen earlier (Rivers and Frankel, 1980). Rivers and colleagues did recognize that dietary vitamin D concentrations may have been excessive in their earlier work. However, when dietary vitamin E concentrations were corrected, similar fatty acid changes again occurred. Hydrogenated coconut oil, which would not readily deplete vitamin E stores, was the source of fat in this latter study. In addition, when GLA (18:3n-6) containing oils were added to the diets, reproductive status

improved. This fatty acid may have improved AA status to some extent by virtue of bypassing the Δ6 desaturase step (Rivers and Frankel, 1980). For more details of these early studies, see Sinclair (1994) and Bauer (1997).

Studies by MacDonald and colleagues found that EFA deficiency resulted in signs similar to those reported by Rivers and coworkers (MacDonald et al., 1983a,b, 1984c). However, one of these studies (MacDonald, 1983b) observed that diets containing 5 percent safflower oil plus 30 percent hydrogenated coconut oil (6.7 percent ME LA, no AA) prevented all clinical signs except reproduction problems in females. Reports from Australia (Sinclair et al., 1979, 1981; McLean and Monger, 1989) indicated that cats maintained for up to 8 years on diets containing 5 percent (as-is) safflower oil did not suffer the severe signs noted by Rivers and Frankel (1980). The Australian cats seemed normal except for some dulling of hair coats and a general inability of females to produce more than two litters. It was speculated that the severity of signs was attenuated by improper amounts of taurine and some vitamins as acknowledged in the earlier studies. Nonetheless, it was believed at the time that amounts of LA that would be adequate for other mammalian species did not maintain cats in optimal health during all life stages. Explanations for these observed differences included the possibility that diets differing in their relative fatty acid profiles or other nutrients may have led to variable capacity of cats to synthesize AA. Indeed, certain n-3 fatty acids such as ALA (Holman and Mohrauer, 1963; Mohrauer and Holman, 1963; Hwang and Carroll, 1980; Monger, 1986) may be involved in regulation of the Δ6 desaturase enzyme. For that matter, AA itself may regulate this enzyme (Whelan, 1996).

Evidence for Limited Δ6 Desaturase Activities

In addition to the above findings, early biochemical evidence of low but existent Δ6 desaturase activities in cats was obtained when production of small amounts of Δ5,8,11-20:3 (20:3n-9) was observed in cats fed LA diets containing no AA (Rivers and Frankel, 1981; Sinclair et al., 1981; MacDonald et al., 1983a). This fatty acid is produced from oleic acid by the same pathway as AA from LA. More recently, limited Δ6 desaturase activity in cats has been confirmed by using sophisticated stable isotope techniques combined with gas chromatography and mass spectrometry (Pawlosky et al., 1994) and appeared when a diet completely devoid of AA was fed. Because Δ6 desaturase activity is limited in cats, feeding diets rich in LA results in a modest accumulation of 20:2n-6 via chain elongation and the appearance of a novel fatty acid Δ5,11,14-20:3. This fatty acid is the result of Δ5 desaturation of 20:2n-6 (Sinclair et al., 1981) and is a hallmark of limited Δ6 desaturase but active Δ5 desaturation when dietary supplies of LA are high (Bauer, 1997).

Dietary LCPUFA and Feline Life Stage

The need for dietary AA for successful reproduction was studied recently by using three groups of cats fed diets containing either 1 percent corn oil and 9 percent hydrogenated coconut oil (calculated to contain approximately 2 percent ME as LA and 10 percent total fat by weight); 3 percent corn oil; or 1 percent corn oil plus 0.02 percent AA before mating and throughout pregnancy (Pawlosky and Salem, 1996). All animals became pregnant, but a high incidence of congenital defects and low viability was found in the 1 percent corn oil group. By comparison, the diet containing 3 percent corn oil without AA supported reproduction. This study showed that queens are incapable of effective reproduction when maintained on a diet low in PUFAs including LA and that the addition of a small amount of AA restored this function. However, because the diet containing 3 percent corn oil without AA also supported reproduction, it was concluded that dietary factors other than AA may be involved. Also, the neonatal kittens from queens fed AA in this study were found to synthesize AA from labeled LA precursor (Pawlosky et al., 1997).

Morris (2001, 2002) also investigated the effect of AA-depleted diets on feline reproduction and confirmed earlier findings that male cats fed diets containing LA, but not AA, are fertile. This work was extended by showing that queens reared from weaning on diets devoid of AA were also fertile. After conception occurred, the queens showed subsequent gains in body weight; however, only one successful pregnancy resulted. Supplementation of these queens with AA did not result in any successful pregnancies. Morris speculated that, except for one or two litters, queens do not need AA but that for additional litters, some other factor is missing for successful reproduction.

Information on the capacity for LCPUFA synthesis in feline tissues has been obtained in a recent series of studies in cats using stable isotopes. In addition to some AA synthesis, adult cats were also found to produce 20:5n-3 and 22:5n-3 (DPA, n-3) in liver and 22:6n-3 (DHA) and 22:5n-6 in brain (Pawlosky et al., 1994, 1997). Of particular interest from these findings is that the final step of desaturation to form DHA may take place only in the nervous system, and not in the liver, of cats.

Independent of site of tissue synthesis, the important question is whether the synthetic capacities of cats for LCPUFAs (whether n-6 or n-3) are adequate for various life stages. Following their earlier study, Pawlosky et al. (1997) fed diets with various amounts of corn oil and hydrogenated coconut oil to cats prior to mating, during pregnancy, and during lactation. Two reference diets that contained AA and DHA were also evaluated. The corn oil diets were capable of maintaining AA concentrations in the developing retina and brain, but only those diets containing DHA could support the high concentrations of DHA generally found in these tissues. Low concentrations of 22:5n-6 were also found, sug-

gesting that kittens have a low capacity to produce this fatty acid as well as DHA. Differences in electroretinograms were observed in all LCPUFA-deficient diet groups compared to control animals fed either 1,100 mg AA·kg^{-1} and 640 mg DHA·kg^{-1} of the reference diet used (calculated from Pawlosky et al., 1997) or a supplemented corn-oil/hydrogenated coconut oil diet containing 200 mg AA·kg^{-1} and 200 mg DHA·kg^{-1} (Pawlosky et al., 1997). The LCPUFA-deficient diets did not provide kittens with an adequate supply of n-3 fatty acids for proper accumulation of neural and retinal DHA during development and thus were inadequate for support of optimal visual function. Conversion of either the n-6 or the n-3 18-carbon precursors simply may not occur to the extent needed in developing or immature cats. Another study using practical diets found the presence of small amounts of dietary AA, EPA, and DHA (i.e., 0.14 percent, 0.02 percent, and 0.03 percent, as-is basis) in combination with high LA (i.e., 4.2 percent as is) resulted in insignificant conversion of ALA to LCPUFAs when supplied as 0.88 percent (as is) in the diets of 19- to 20-month-old cats (Chew et al., 2000). Thus, the picture emerging is that, for maintenance or normal conception, adult cats may not require an exogenous source of AA. However, for proper gestation, development, lactation, and growth, metabolic demands are such that provision of appropriate exogenous amounts of both n-6 and n-3 LCPUFAs is advised and thus conditionally essential.

Immune, Inflammatory, and Platelet Cell Functions

Little is known about possible antiinflammatory and immunomodulatory function of dietary n-3 PUFA in cats. One recent report compared effects of plant versus marine-based n-3 fatty acid-containing diets (i.e., flaxseed vs. fish oil) at two total fat concentrations. Dietary n-3 PUFAs from either fish or flaxseed oil decreased skin inflammatory response to histamine to the same extent. In contrast, dietary fish oil significantly decreased LTB_5 concentrations (Chew et al., 2000). Neither of the n-3 fatty acid sources affected the large variety of immune parameters investigated including delayed-type hypersensitivity responses, interleukin 2 (IL-2) production, or lymphocyte proliferation. Only those cats fed the fish oil diets showed lower B cell subpopulations and lower total T and T helper cell subsets. It was concluded that flaxseed may be less immunosuppressive in a lower-fat diet (14 percent) than it is in a higher-fat diet (Chew et al., 2000). These findings are likely the result of limited conversion of flaxseed ALA to LCPUFAs compared to feeding pre-formed LCPUFAs. LCPUFAs are well known to more characteristically modify inflammatory and immune functions in mammalian species than their 18-carbon precursors.

Platelet function tests using platelet-rich plasma from a small group of cats fed diets containing approximately 75 percent moisture and 27.7 percent (DM) crude fat varying in corn oil, choice white grease, and menhaden fish oil to modify total n-6:total n-3 ratios (25:1, 12:1, and 1.3:1) have been conducted. The diets also contained turkey, turkey liver, and rice. The cats had been fed one of the three diets for 16 weeks. Animals consuming the diet with the lowest ratio (highest amount of fish oil) were observed to have decreased platelet aggregation and platelet activation, and increased bleeding times. No differences were seen in activated partial thromboplastin time, one-stage prothrombin time, and fibrinogen concentrations as measured in whole-blood samples from the animals (Saker et al., 1998). It was concluded that prolonged ingestion of enriched n-3 fatty acid diets from fish oil resulted in detrimental effects at the dietary dosages examined. Specific amounts of the n-6 and n-3 fatty acids used in the diets were not reported in this study.

REQUIREMENTS, RECOMMENDATIONS, AND ALLOWANCES

Table 5-1 lists the fatty acid abbreviations used in describing the recommendations for both n-6 and n-3 fatty acid families.

Recommendations for dietary fat types for dogs and cats have taken into consideration the consensus of several expert workshops as well as the body of literature available comparatively and specifically for the target species. The notions that potential benefits are to be gained in human adults by reducing dietary n-6 PUFAs, whereas increasing the amounts of n-3 PUFAs benefits cardiac health and that increasing n-3 PUFAs in infants promotes development, have been considered. However, it must be borne in mind that despite several similarities in lipid metabolism among dogs, cats, and humans, distinct differences also exist. For example, unlike humans, dogs and cats are "high-density lipoprotein mammals" expressing atherogenic resistance. Thus, they are able to tolerate high dietary fat concentrations. Further, among mammals, cats are unique regarding their fatty acid metabolism. Being fur bearing, a beneficial response relating to skin and coat conditions has been

TABLE 5-1 List of Abbreviations of Selected Fatty Acids and Fatty Acid Terminology

Fatty Acid Abbreviation	Trivial Name	Omega Notation	Fatty Acid Series
PUFA	Polyunsaturated fatty acid	—	General
LCPUFA	Long-chain polyunsaturated fatty acid	—	General
LA	Linoleic acid	18:2n-6	n-6
AA	Arachidonic acid	20:4n-6	n-6
ALA	α-Linolenic acid	18:3n-3	n-3
EPA	Eicosapentaenoic acid	20:5n-3	n-3
DPA	Docosapentaenoic acid	22:5n-3	n-3
DHA	Docosahexaenoic acid	22:6n-3	n-3

shown in dogs fed high LA plus zinc-containing diets (Marsh et al., 2000), and high dietary PUFAs generally appear to be associated with improvements in skin and coat scores (Rees et al., 2001). In guinea pigs, it has been found that more than 46 percent of an oral dose of radiolabeled ALA was associated with skin and fur lipids after 48 hours (Fu and Sinclair, 2000). When labeled LA was fed, approximately two-thirds of the label was found in the skin plus fur fractions (Fu et al., 2001). These data indicate that a large portion of the dietary 18-carbon PUFAs are present in skin and fur. They also point to the possibility that, after 48 hours of feeding, there was little metabolism of LA to the more highly unsaturated fatty acids (Fu et al., 2001). These findings are consistent with data in dogs in which AA enrichment of neutrophil membranes of animals fed either 2.5 or 27.4 percent ME as LA was equivalent (Waldron, 1999). In view of their fur-bearing nature and existing information, a decrease of dietary LA in dogs and cats similar to that recommended for humans is not believed appropriate. For humans, the Nutrition Committee of the American Heart Association has recommended that dietary LA content not exceed 10 percent ME. This value was based, in part, on studies of artificially induced tumors in mice in which diets containing either 17 or 25 percent ME LA increased tumor weight (Rose et al., 1993, 1994). Furthermore, participants at a recent expert workshop convened in the United States to consider human dietary needs recommended that LA not exceed 3 percent ME for humans (6.67 g in a 2,000-kcal diet) (Simopoulos et al., 1999). The recommendations made here for dogs and cats diverge somewhat from these recommendations for humans. In dogs and cats, higher amounts of LA are considered safe and efficacious (see Chapter 15).

With respect to cats, given their poor efficiency of LA conversion to longer-chain PUFAs, a modest dietary supply of AA and an upper threshold of LA somewhat lower than those for dogs are recommended.

Finally, recommendations for increasing the n-3 fatty acid content in both dog and cat diets has been made. These are based on the competitive but nonlinear hyperbolic relationship versus n-6 fatty acids that has been found for rats, humans, and dogs (Lands et al., 1990, 1992; Bauer et al., 2002); stable isotope studies with cats during development; estimates of adequate intakes from modern-day pet food fatty acid compositions; and the body of literature already described. Addition of n-3 PUFA to dog and cat diets, while maintaining current amounts of n-6 fatty acids for adults, is therefore recommended (see Chapter 15). The SUL values, where shown, are those believed to be safe based on specific data available for dogs and cats.

Essential Fatty Acids for Dogs and Cats

Both n-6 and n-3 fatty acids are essential for dogs and cats. In some cases, the requirement can be met using LA and ALA, but there are some important exceptions depending on the physiologic state of the animal. Thus, some fatty acids are considered conditionally essential in a number of instances. The following discussion is focused on both absolute and conditional requirements for adult maintenance, growth, and reproduction and lactation.

Foremost among the EFAs is the dietary requirement for n-6 fatty acids in the form of LA for both dogs and cats.

Under certain conditions, such as growth and reproductive performance of queens, modest dietary provision of AA is also necessary. Early studies have shown that signs of EFA deficiency in puppies and young dogs were reversed when 2 to 6 percent of energy was provided by LA or AA (Hansen and Weise, 1951; Wiese et al., 1966). This amounts to 0.94 to 2.82 percent DM given an energy density of 4.0 $kcal \cdot g^{-1}$ DM metabolizable energy. Although AA also shows EFA activity, dogs can synthesize sufficient amounts of it from LA. Thus, only LA must be supplied to dogs. For cats, dietary LA may also be sufficient to supply the essential n-6 fatty acids needed for adult maintenance and for conception to occur. However, maintenance of normal pregnancy and neonatal growth and development of cats requires a source of the preformed long-chain n-6 fatty acid, AA.

With respect to the n-3 fatty acid ALA, definitive studies on its essential nature have not been conducted in dogs and cats. Nonetheless, work in other species indicates that the provision of small amounts to adult dogs will support health, cell turnover, and cell function. Conversion of ALA to EPA occurs in dogs and cats, but its conversion to DHA is limited. However, based on studies in other species, the variability of these conversions is such that some individuals may show no detectible conversion of ALA to DHA. For adult maintenance, conversion of ALA may be sufficient to provide long-chain n-3 PUFAs (i.e., 20- and 22-carbon acids) because the amount needed is small. However, under special circumstances such as growth, reproduction, or lactation, adequate and recommended amounts of long-chain n-3 PUFAs are indicated in the tables. A dietary requirement for them remains to be demonstrated, and only adequate intakes, and recommended amount based on the existing literature have been estimated at this time.

DOGS

Fat Content of Diets: Preferences, Minima, and Maxima

Diets with a wide range of fat concentration appear to be consonant with good health in dogs. However, as noted earlier, when diets high in total fat are formulated, care must be taken to ensure the adequate intake of protein, minerals, and vitamins. Proper formulation of diets containing fat thus requires adjustment for its high energy value (Cowgill, 1928). Published literature on the preferences of dogs for various sources of dietary fat is sparse, but it appears that dogs adapt to a fairly wide range of fat types and amounts. It has been noted that dogs may prefer animal fats for reasons ascribed

to flavor and added palatability (Rainbird, 1988; Earle and Smith, 1993). Also, it should be noted that dogs will eat rancid fat, but this is not a recommended practice. One early study reported no adverse effects of feeding partially hydrogenated soybean oil previously used for commercial deep fat frying to four dogs for 54 weeks (Nolen, 1973). However, more recently, retinal degenerations and lipofuscin accumulation in intestinal smooth muscle and neurons have been documented to be associated with vitamin E deficiency in a group of adult hunting dogs that had been fed food scraps with a high content of red meat and fat from restaurant waste (Davidson et al., 1998). Feeding predominantly meat and table scraps has been consistently associated with naturally occurring vitamin E deficiencies (Hayes et al., 1970a,b). Ingestion of oxidized fats also has been associated with reduced weight gain and body fat content, decreased serum vitamin E, and alterations of some cellular measures of immune function (Turek et al., 2000).

As noted, dogs have a wide tolerance for dietary fat. However, depending on the EFA concentrations of fat sources used and on provision of sufficient nutrient density, minimal amounts of total fat can suffice. Thus, strictly speaking and beyond the need to provide appropriate EFAs, an MR of total fat for dogs and cats is unknown. Dogs can be maintained by feeding dry-type diets containing 5 to 8 percent total fat in dry matter, and many canned foods for adult maintenance contain in excess of 10 percent on a DM basis (Kraybill and Curtis, 1938; Anonymous, 1998a,b, 2000). However, in practice, a minimal fat content of 5 percent of DM has been suggested for commercial foods (Linton, 1934), and this amount generally allows for the inclusion of adequate EFAs with most fat sources. Nonetheless, some caution is needed. For example, using beef fat (tallow) exclusively is not advised because of its low LA content. In some cases, its combination with other pet food ingredients that contain fat, such as corn, may result in a formulation that contains enough LA and ALA to maintain nutritional adequacy. However, this is not always the case.

Maximal fat contents of diets for dogs may be reasonably high without adverse effect, although there are some exceptions. Several canned veterinary specialized products in which dietary protein is modestly reduced by fat substitution are among the diets whose amount of energy from fat ranges from 50 to 60 percent ME. Diets with 10 to 24 percent fat have been fed for 2 years without identified adverse effects (Morgan, 1935, 1940), and other studies have reported tolerance for 40 percent fat (Ivy, 1936; Axelrod et al., 1951). Also, diets containing 81 g total fat per 1,000 kcal (calculated from data provided) have been fed to sled dogs without evident problems (Adkins and Kronfeld, 1975; Downey et al., 1980). However, when dogs were fed a low-protein, high-fat diet containing 7 g of lean meat and 10 g of lard per kilogram of body weight along with 50 g sucrose plus vitamin and mineral supplements, pancreatitis was induced (Lindsay et al., 1948). This diet contained only 6 percent ME protein and 78 percent ME fat (calculated from Lindsay et al., 1948) and facilitates defining a SUL for dietary fat. By comparison, Meyer et al. (1979) fed 3- to 5-month-old puppies diets containing from 8 to 14 g fat·kg BW^{-1} for 3 months without any negative effect on pancreatic activity. One other precaution is that sedentary adult dogs have a greater tendency to become obese when fed high-fat diets ad libitum compared to high-carbohydrate diets (Romsos et al., 1978), although a slight restriction in food intake will prevent the development of obesity when high-fat diets are fed. Finally, hypercholesterolemia in dogs occurs when animals are maintained on high-fat diets (ca. 60 percent ME) (Kronfeld et al., 1979; McAlister et al., 1996). However, it is unlikely that this particular alteration is associated with any serious metabolic consequence because the excess cholesterol is primarily in the esterified form and associated with high-density lipoprotein fractions (McAlister et al., 1996). Because high-density lipoproteins are considered beneficial relative to coronary artery disease risk, the likelihood of atherogenesis in dogs is minimal at the plasma cholesterol concentration observed. This phenomenon may, in part, explain this species' generalized resistance to developing coronary artery disease and stroke (Bauer, 1996; Wagner et al., 1999).

Growth

Dietary amounts of total fat needed for growth of young dogs are greater than those needed for adult maintenance yet likely less than that in canine milk consumed during suckling. However, a total fat SUL for canine growth is similar to that for adults (see Adult Maintenance section). The requirements for growth are likely to lie between the nutrient profiles of canine milk and adult maintenance needs. When milk total fat content (Bauer et al., 2000; Lepine et al., 2000) is arbitrarily multiplied by a factor of 0.30, the result is remarkably consistent with total fat needs for growth reported previously (NRC, 1985). Thus, a recommended allowance (RA) of 8.5 percent dry matter (DM) (ca. 18 percent ME) for growth is unchanged from its earlier estimate. Using a similar calculation for the individual fatty acids, an estimated adequate intake for LA of 1.18 percent DM (2.5 percent ME) can be calculated, which is also similar to previous recommendations [i.e., 2.43 percent ME (AAFCO, 2003) and 2.3 percent ME (NRC, 1985)]. Accordingly, an estimated adequate intake (AI) for ALA has been calculated to be 0.07 percent (DM) (0.15 percent ME). The LA:ALA ratio resulting from these two calculations (based on percent ME) approximates the high value of the range recommended for reproductive performance at less than 17. These amounts are presumed to be adequate at this time. Using these values and adding a 10 percent safety margin, the RAs are 1.3 percent DM for LA and 0.08 percent DM for ALA with an LA:ALA ratio of 16.3. Modestly higher ALA contents will result in a lower LA:ALA ratio that is also within the recommended

range (see Table 15-3, footnote f). It is important to note that the use of milk fatty acid composition data as a basis to determine the AI values for PUFAs takes into consideration that LCPUFAs are also present in canine milk. Thus, if only LA and ALA (no n-3 or n-6 LCPUFAs) are provided in a diet formulated for growth, adequate amounts of LA and ALA needed may be greater than those estimated above.

Given their presence in canine milk, it seems reasonable that some estimate of AI for n-3 LCPUFAs also must be made. For DHA, the AI is approximately 0.030 percent DM (0.028 percent DM) based on milk composition and factored as above. Similarly, the AI of AA should be in the range of 0.03 to 0.05 percent DM. Because EPA is not known to offer health benefits to very young dogs, AIs for EPA are low and should not exceed more than 0.03 percent DM. Support for using this approach exists in that the values calculated by factoring average milk composition values in the above fashion compare favorably with those recommended by the recent Workshop on the Essentiality of and Recommended Dietary Intakes (RDIs) of Omega-6 and Omega-3 Fatty Acids in which adequate intakes for infant formulas and diets were delineated (Simopoulos et al., 1999). However, it must be emphasized that these are, at best, only estimates of AI. There are no published studies available to define precisely the MR, AI, or RA values for these fatty acids.

Adult Maintenance

The RA of total dietary fat for adult dogs is 11.7 percent ME (5.5 percent DM in a 4,000 kcal·kg^{-1} DM diet). There is no new evidence to recommend changing this value from earlier estimates (Linton, 1934), and lesser amounts may depress food intake. The MR for total fat may actually be lower than this value, but it has not been specifically determined to date. If so, the AI for total fat may be as low as 4 percent DM, but only under circumstances in which total food intake is not affected (Campbell and Phillips, 1953). This latter value is deemed adequate and should be considered speculative until additional studies are performed. The safe upper limit (SUL) for total dietary fat is approximately 70 percent ME or 82.5 g per 1,000 kcal ME (Downey et al., 1980; Adkins and Kronfeld, 1982). At higher fat concentrations, hypertension and obesity were induced in dogs by feeding 2 pounds cooked beef plus 1 can of dog food daily for 5 weeks (Rochhini et al., 1987). The amount of fat in this diet was estimated to be approximately 95 g total fat per 1,000 kcal ME. Another study, noted earlier, induced pancreatitis in dogs using approximately 92 g per 1,000 kcal ME (Lindsay et al., 1948). Thus, the SUL for total fat is based on a safety margin of about 10 percent less than the amount reported to have induced pancreatitis and is consistent with the data of Adkins and Kronfeld (1982) and Downey et al. (1980). Many practical diets for healthy dogs will typically contain between 22 and 60 g per 1,000 kcal ME total fat, well below the SUL, especially because protein to calorie ratios are a problem in 4,000 kcal ME·kg^{-1} diets when total fat exceeds 82.5 g per 1,000 kcal.

When formulating canine diets, fat sources and other components should be chosen to include LA at an RA of 2.34 percent ME (1.1 percent DM). There is some evidence to indicate that the MR for LA is less than 1.1 percent DM, with adequate amounts approximating 0.6 percent DM (Bauer et al., 2002), but further work will be needed to confirm this possibility. For growing puppies, 1 percent of ME did not seem to be adequate although 2 percent was sufficient to prevent deficiency. This latter amount is approximately 0.95 percent DM in a diet containing 4 kcal·g^{-1} ME and is recommended as an AI. Using a safety margin of approximately 10 percent, the RA for diet formulation, given a nutrient density of 4,000 kcal·kg^{-1}, is thus 11 g·kg^{-1} DM LA (Table 15-5). It should be noted that, while epidermal ceramide EFAs are enriched in LA, tissue cell membranes generally are rich in AA. Because dogs readily convert LA to AA, a portion of the dietary LA amount will be used for AA synthesis and utilization. The RA for LA thus should be minimally sufficient to reliably maintain normal physiologic functions of all organ systems. Higher amounts of total fat, LA, or other fatty acids are also acceptable to improve palatability of food or hair coat gloss. However, definitive studies on the amounts and types of dietary fats needed to maintain or improve hair coat quality have not been published to date. When fat content is increased, calculations regarding the nutrient-energy ratio should always be verified.

Regarding an SUL for LA, population intakes of LA range from 2.4 to 13.3 percent ME based on recent analyses of 27 separate commercial dog foods (calculated from Roudebush, 2001). Results from long-term studies in dogs have not been published, but one report on the incidence of naturally occurring mammary cancer in rats found no difference in incidence in tumor-free and tumor-bearing animals fed diets with 13.8 percent LA in DM (Appleton and Landers, 1986). For dogs, the SUL of LA may approach this value, depending on the ALA or EPA content of the diet. This is because high amounts of LA may be metabolically balanced by the presence of ALA in the diet as a result of competitive interactions with LA for metabolism. The SUL also may be increased by the presence of EPA or lowered by the presence of AA. Unfortunately, quantitative data have not yet been published on these types of interactions in canine species. Consequently, the SUL for LA is based on the available data and the hyperbolic and competitive relationships among the various n-6 and n-3 acid types recently reported for dogs (Bauer et al., 2002). Given the above information, the SUL for LA is estimated at 16.3 g per 1,000 kcal (13.8 percent ME). An ALA concentration that equals or exceeds 0.25 percent DM (0.55 percent ME) can be subsequently calculated and used as a guideline for metabolic balance of these two fatty acids so that the ratio of LA to ALA is within the recommended range (see Table 15-5, footnote e). Amounts of LA in excess of this amount are not recommended for long-term feeding.

The RA, AI, and SUL for ALA are based on data available on n-3 PUFAs in experimental animals and humans for development as reviewed above. Recent recommendations for laboratory animals (Reeves et al., 1993) and supportive studies in dogs demonstrate that ALA provides substrate for cellular EPA synthesis as well as plasma accumulation of DPA (n-3) (Bauer et al., 1998; Bibus and Stitt, 1998). DPA is then transported via plasma and ultimately converted to DHA in retina and neurologic tissues of normal dogs. DPA is thus an important source of DHA for neurological tissue (Alvarez et al., 1994). In this way, ALA acts as a precursor of n-3 LCPUFAs. Estimates of existing average daily intakes of ALA in human populations range from 0.35 to 0.7 percent ME (Anonymous, 1992c). For adult dogs, the MR for ALA is likely to be less than the MR for fetal or neonatal development but an exact value has not been determined. Nonetheless, an RA of approximately 0.044 percent DM (0.09 percent ME) for dietary ALA at an LA concentration of 1.1 percent DM (2.34 percent ME) is recommended. Because of competitive metabolic interactions with LA (Dunbar and Bauer, 2002), all recommendations for ALA (i.e., RA, AI, SUL) likely depend on the LA content of the diet. Thus, if considerably more than the RA of LA is present in a diet (which is often the case in many practical diets), the addition of more ALA may be prudent to achieve a metabolic balance of derived n-3 and n-6 20-carbon fatty acids for eicosanoid synthesis in healthy dogs. This is one instance in which the ratio of LA to ALA should be considered. A range for this ratio of 2.6 to 26 is presumed safe based on evidence to date. It includes a margin of safety of approximately 10 percent at both extremes.

A specific requirement for long-chain n-3 PUFAs (EPA and DHA) in adult dogs has not been identified to date. Despite their metabolic roles in inflammation and neural development in several species, direct evidence of a requirement for pre-formed sources of these fatty acids in adult dogs is not available. The same proviso applies to defining a dietary minimum for long-chain n-6 PUFAs (i.e., AA) in adult dogs. However, an AI of 0.11g per 1,000 kcal of combined EPA and DHA for overall health is recommended based on studies in other species including humans, and pet food usage data. Bear in mind, however, that individual amounts of EPA and DHA will vary among sources typically used. Thus, small variations in amounts of both of these n-3 LCPUFAs are acceptable until more data become available (Table 15-5). Safe upper limits of long-chain n-3 PUFAs have been inferred as a result of evidence of impaired cellular immunity when dogs were fed diets containing 3.13 percent ME n-3 LCPUFAs at an n-6 PUFA content of approximately 4.8 percent ME for 12 weeks (Wander et al., 1997). Long-term studies of Greenland Eskimo populations consuming 9 $g \cdot d^{-1}$ of long-chain n-3 PUFAs did not discover any adverse effects. This amount is approximately analogous to 2.6-3.8 percent ME. No data on long-term effects in dogs are available, and many short-term studies have focused only on fatty acid ratios, with actual amounts not reported. Other studies in dogs used high doses for short periods (Waldron, 1999; Brown et al., 2000; Hall et al., 2002). The upper limit for the sum of EPA and DHA for humans proposed by the BNF Task Force (Anonymous, 1992b) was 2 percent ME with a maximal margin of safety of total n-3 PUFAs of 4.5 percent ME. The former value does not include amounts of DPA (22:5n-3) present in many naturally occurring sources, but the latter value does. However, the studies by Wander et al. (1997) and Hall et al. (1999) of normal beagle dogs would appear to place the SUL at between 2.1 and 2.6 percent ME of a diet containing 4,241 $kcal \cdot kg^{-1}$ DM and 42.6 percent ME as total fat. Decreasing the upper value of this range by approximately 10 percent as a margin of safety establishes an SUL for total n-3 LCPUFAs in dogs of approximately 2.4 percent ME (i.e., 2.8 g per 1,000 kcal).

Gestation and Lactation

The requirement of total dietary fat necessary to support gestation and lactation of dogs is greater than that for maintenance (Siedler and Schweigert, 1952; Ontko et al., 1957). However, studies precisely establishing the MR for total fat have not been conducted to date. There are data to indicate that 7.7 percent total fat, as is, resulted in successful reproductive performance (Siedler and Schweigert, 1952), and this amount provides the basis for the AI. In view of these findings, by considering moisture content and typical fat digestibilities of dry extruded-type diets, the AI and RA values of 8.5 percent DM should provide sufficient dietary fat for canine reproduction. Although a MR of LA for reproduction has not been established, an AI for LA on a dry matter basis would be expected to be somewhat lower than that for growth (i.e., 1.1 percent DM vs. 1.18 DM assuming a nutrient density of 4,000 $kcal \cdot kg^{-1}$). If so, an AI for ALA can be calculated as approximately 0.07 percent DM within the recommended range of dietary LA:ALA ratio (see Table 15-8). Estimates of the RAs for EFAs based on quantitative measurements of physical growth of maternal tissues and fetuses during pregnancy (Hytten and Leitch, 1971) have been calculated by the Food and Agricultural Organization-World Health Organization to be 1-1.5 percent ME as an additional total EFA requirement for pregnancy With this calculation in mind, the RA for LA may easily be 0.42 percent ME higher than that for maintenance, resulting in a total LA energy recommendation of 2.76 percent ME (1.3 percent DM in a 4,000 $kcal \cdot kg^{-1}$ DM diet). At this LA value, the RA for ALA may have to be minimally increased by 0.06 percent ME over that recommended for maintenance (i.e., total ALA of 0.17 percent ME or 0.08 percent DM in a 4,000 $kcal \cdot kg^{-1}$ DM diet). Bear in mind that more (up to 0.5 percent DM) would also be appropriate given the recommended range of LA:ALA ratios. Because of competition between LA and ALA for metabolism, the LA:ALA ratio should range between 2.6 and 16. This range is not as wide as that for main-

tenance, thereby helping ensure the availability of 18-carbon n-3 ALA for subsequent elongation. With respect to the LCPUFAs, preliminary studies on the fatty acid composition of canine milk have provided some guidance. One recent study reported that AA and DHA are present in amounts similar to those in other mammals (AA, 1.22 percent; DHA, 0.7 percent of total milk fat) (Lepine and Kelley, 2000), and another study has found relatively higher AA and lower DHA (1.82 percent and 0.08 percent of total milk fat, respectively) (Bauer et al., 2000). The extent to which milk fatty acids can be modified by diet is unknown in dogs, but data in humans, rats, and pigs indicate a dietary influence on milk fatty acid profiles (Huang et al., 1992; Ruan et al., 1995; Makrides et al., 1996). Given the benefits of providing pre-formed amounts of both DHA and AA in human premature infant formulas and the conditionally essential nature of these fatty acids in neurological development (Carlson et al., 1993; Huang and Craig-Schmidt, 1996), it is expected that small amounts of dietary DHA during gestation would be expected to ensure fetal development as well as subsequent lactation. However, not enough information exists at present to define an MR for LCPUFAs during gestation and lactation in dogs. Modest amounts (i.e., 0.05-0.10 percent DM) are considered adequate at this time. The SUL values are the same as for maintenance.

CATS

Fat Content of Diets: Preferences, Minima, and Maxima

Large cats in the wild may obtain 60 percent of their energy from dietary fat, and diets containing 67 percent ME as fat are efficiently utilized (Scott, 1968). In domestic cats, reasonably high-fat diets from either animal or plant sources have been fed using purified diets containing 25-30 percent total fat and 30-40 percent protein (as is). By comparison, dry-type, extruded cat foods typically contain 8 to 13 percent fat DM. Both type and amount of dietary fat affect food acceptability to cats. Generally, higher-fat diets appear to be more palatable than low-fat diets (Greaves, 1965; Kendall, 1984; NRC, 1986). However, diets containing 25 percent total fat were preferred to diets with either 10 percent or 50 percent total fat. Beef tallow was selected over butter and chicken fat, but no preference was evident among beef tallow, lard, or partially hydrogenated vegetable oil (Kane et al., 1981).

Type and amount of fat also appear to affect growth in kittens. Scott (1966) found satisfactory performance in kittens fed diets containing 22 percent fat. Diets with 25 percent hydrogenated coconut oil were found to be unpalatable and failed to support growth. By contrast, hydrogenated beef tallow did support growth in kittens over a 7-week period, although fatty acid deficiency developed. The difference between these fats was attributed to palatability, because consumption of the hydrogenated beef tallow diet was markedly higher than that of the hydrogenated coconut oil diet. Acceptance of the latter could be improved by adding amounts of EFAs from safflower oil and poultry fat (MacDonald et al., 1983b, 1985). Kittens chose nonhydrogenated beef tallow over chicken fat (3:1), but no significant difference was found between 35 percent total fat diets with hydrogenated tallow versus regular beef tallow (MacDonald et al., 1983a).

Medium-chain triacylglycerols are poorly accepted by cats. When an MCT preparation enriched in caprylic acid (C8:0) was offered, young cats would not eat again after first tasting the diet. Caprylic acid between 0.1 and 1 $g \cdot kg^{-1}$ diet caused the diet to be unpalatable (MacDonald et al., 1985).

As in dogs, because the ME content of fat is approximately 2.25 times that of protein or carbohydrate, changes in fat amounts will modify the caloric density of a diet. Adjustment of other nutrient concentrations, particularly protein, vitamins, and minerals, must be made in order to maintain appropriate overall nutrient intakes.

Maximal fat contents of balanced diets for cats may be reasonably high without any known adverse effects (total calories notwithstanding). Many feline diets presently being fed contain approximately 50 percent or more of total energy from fat. Some diets for adult animals that are designed to modestly decrease protein amount contain more than 70 percent ME total fat. These values are consonant with estimates of fat utilization in this species.

The recommended safe upper limit (SUL) of total dietary fat is approximately 70 percent ME (82.5 g per 1,000 kcal), although practical diets generally span a wide range from 22 to 55 percent ME, depending on cat food category.

Growth

Dietary amounts of total fat needed for growth of young cats are greater than those needed for adult maintenance. The needs for growth are likely to lie between the nutrient profiles of queens' milk and adult feline maintenance. Again, when the total fat content of milk (Lepine and Kelly, 2000) is multiplied by a factor of 0.3, the result is similar to the previous total fat recommendations for growth. Thus, the RA of total fat for growth is 9 percent DM (assuming 4,000 $kcal \cdot kg^{-1}$ DM). Using this approach for individual fatty acids, an estimated amount of LA for growth would be 1.3 percent DM, which is somewhat higher than earlier recommendations. This amount may reflect a surplus of dietary LA, resulting in its enrichment in queens' milk. Thus, the RA of LA is more likely to be similar to those amounts needed for gestation and lactation (i.e., 0.55 percent DM of a 4,000 $kcal \cdot kg^{-1}$ DM diet). An estimated supply of ALA has been calculated to be 0.02-0.03 percent DM at the recommended LA level. This amount is presumed adequate at this time, although no requirement has been established for this nutrient in growing kittens. With respect to the LCPUFAs, an AI of 0.05 percent DM for AA is presumed adequate

based on milk composition factored as above. However, this amount also seems excessive in terms of an adequate intake because it is 2.5 times higher than amounts of AA presumed adequate for reproductive performance. It may be that this higher concentration of AA reflects the possibility that the diet used in the Lepine and Kelly study (2000) largely exceeded the MR for AA. Until more information is known, no changes in the AI and RA values of AA from the amounts for gestation and lactation are recommended (i.e., 0.02 percent DM of a 4,000 kcal·kg^{-1} diet). For DHA, 0.01 percent to 0.02 percent DM is presumed adequate, but little information is available in cats on this or other n-3 LCPUFAs. It is of interest that values calculated by factoring average milk composition in the above fashion compare only reasonably well with previously estimated requirements for cats, as noted above, and for human infants recommended by a recent workshop on the RDIs of ω-6 and ω-3 fatty acids (Simopoulos et al., 1999). Compared to dogs, many of the PUFA values calculated using feline milk composition tended to overestimate previous recommendations when factored by 0.3. This may be due, in part, to the limited information presently available on the fatty acid composition of feline milk or other errors associated with this approach. It must be emphasized that values based on the few existing reports of milk fatty acid composition discussed here have, at best, provided only a first approximation of AI in puppies and kittens for growth. This approach has not been established as reliably providing such estimates to date or establishing MR or RA values for these nutrients.

Adult Maintenance

Except for some data on the requirement for AA, studies determining the MR for total fat and other EFAs have not been conducted specifically in cats. Thus, for the most part, only AIs and RAs have been defined. It is recommended that cat foods for adult maintenance minimally contain 9 percent total fat on a DM basis, which is also the AI. Fat sources and other components should be chosen to include an RA for LA of 0.55 percent (DM). The MR for LA may be lower than this value, but specific data are not available on this topic and earlier estimates of the MR do not appear to be well substantiated (NRC, 1986). Thus, a 10 percent safety margin has been added to previous estimates. When stipulating a nutrient density of 4,000 kcal·kg^{-1}, the targeted RAs for diet formulation would be approximately 22.5 g total fat per 1,000 kcal and 1.4 g LA per 1,000 kcal. Feline requirements for LA are expected to be lower than those for dogs because, unlike dogs, very little LA is used for LCPUFA synthesis in cats. Nonetheless, these concentrations are sufficiently reliable for maintaining normal adult physiologic function.

There are few data defining an SUL of LA. One study supplemented an EFA-deficient diet with 5 percent safflower oil and found considerable amounts of the chain elongation product of LA (20:2n-6) in both plasma and liver tissues (MacDonald et al., 1983a). This fatty acid accumulates when large amounts of LA are fed. However, it has no known physiologic function, and any possible untoward effects of it or its metabolite Δ5,11,13- 20:3 have not been reported. By assuming an average LA concentration value for safflower oil and the available data used in the MacDonald et al. (1983a) study, the LA content of the diet used in this study has been estimated to be 37 g·kg^{-1}. Typical analyses of present-day cat foods supplied by several manufacturers show that these products contain nearly 60 g LA·kg^{-1}, with most products in the range of 32-47 g. On this basis, such amounts of dietary LA are not expected to produce an adverse effect. An SUL for dietary LA of 13.8 g per 1,000 kcal seems prudent at this time.

The MR of ALA for cats also has not been determined experimentally. In the absence of any significant Δ6 desaturase activity, ALA would not be converted to n-3 LCPUFAs in significant amounts. Some conversion may exist if diets are completely devoid of n-3 LCPUFAs. However, a metabolic requirement for dietary ALA has not been shown to date in feline species.

Recommendations and allowances for AA are based on the available literature including the reported low biosynthetic capacity of cats for this fatty acid. Earlier it was noted that a specific requirement of AA for feline maintenance either may not exist or appears to be quite low. In view of this phenomenon and recent stable isotope data on the existence of Δ6 desaturase in feline tissues, conversion of LA to meet the metabolic need for AA may be adequate in a majority of adult cats. Thus, for feline maintenance, intake of 0.02 g AA·kg^{-1} DM is presumed adequate rather than required in adults. However, it is not known whether all adult cats are capable of sufficient AA synthesis. Thus an RA of 0.06 g AA·kg^{-1} DM has been set to address this possibility. Also, it should be noted that a modest increase of dietary AA may be necessary when long-chain n-3 fatty acids are present (MacDonald, 1984b; Goustard-Langlier et al., 1999). Thus, although AA may not be required in adults, care should be taken to provide this fatty acid when diets contain high amounts of n-3 LCPUFAs (see Table 15-12 for relative amounts of AA and EPA + DHA recommended). Finally an SUL of AA for cats of 2 g·kg^{-1} (0.2 percent DM) is believed prudent at this time.

Studies establishing requirements for long-chain n-3 PUFAs (EPA and DHA) in adult cats have not been performed. Theoretically, an argument could be made for some requirement given the low Δ6 desaturase activities in this species. If so, amounts needed would be quite small and of an order of magnitude similar to that for AA. Nonetheless, at present there are no data supporting a requirement for n-3 LCPUFAs for feline adult maintenance. An AI of 0.1 g (EPA + DHA) per kilogram of DM diet containing 4,000 kcal·kg^{-1} DM appears reasonable at this time.

Gestation and Lactation

On a percent ME basis, amounts of total dietary fat recommended for gestation and lactation of queens are similar to those for maintenance. However, absolute intakes will be greater because of increased energy needs overall. Thus, the RA for total fat of 9 percent DM (MacDonald et al., 1984c) remains because there are no new data to warrant modification of that value at this time. EFAs will similarly be provided in this fashion so the RA of LA may need not exceed that needed for maintenance (i.e., 0.55 percent DM of a 4,000 kcal·kg^{-1} diet). The RA for AA at 0.02 percent DM is unchanged from previous estimates. This value is considerably higher than the adult maintenance AI value described for AA. However, recent studies have used this amount successfully for reproduction (Pawlosky et al., 1997), and the use of lower amounts or the absence of AA entirely may lead to problems during repeated breeding (Morris, 2001). With regard to the n-3 acids, an AI of 0.02 percent DM for ALA has been estimated specifically to supply some substrate for limited n-3 LCPUFA synthesis. Practical diet formulations typically contain small amounts of these LCPUFAs, and their synthesis may occur only in cases where the concentrations of LCPUFAs in foods are essentially zero (Pawlosky et al., 1994). Thus, small dietary concentrations of n-3 LCPUFAs are probably a more significant source of DHA and EPA than ALA for fetal and neonatal development. In the latter case, there may be no actual need for dietary ALA. However, further study is needed.

With respect to LCPUFAs, a preliminary study of the fatty acid composition of queens' milk has provided some guidance. One recent study reported that AA and DHA are in a range similar to other species (AA, 0.59 percent; DHA, 0.21 percent of total milk fat) (Lepine and Kelley, 2000). It is expected that small amounts of dietary AA and DHA during gestation would ensure fetal development and subsequent lactation. For AA, the AI and RA are greater than those for adult maintenance. For DHA and EPA, there is no information available to presently define an MR for this life stage. Until new information is available, modest amounts (i.e., 0.01-0.03 percent DM) are presumed adequate at this time, primarily from DHA rather than EPA (see Table 15-14).

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6

Protein and Amino Acids

BASIC CONCEPTS

Introduction

Dogs have been used as a model for the study of human nutrition for nearly two centuries. Magendie (1816) was the first to demonstrate that protein was essential for life by showing that olive oil or sugar alone would not support life, but if protein was added, the dogs were in better condition for a much longer period of time. These early experiments and many others were confounded by the lack of knowledge and appreciation of the need for essential micronutrients. Nevertheless, it was clearly understood that protein was essential in the diet. The Magendie Commission was appointed in 1815 to evaluate the nutritive value of gelatin. In 1841, it reported (cited by McCollum, 1957) that dogs could not be maintained when fed gelatin alone. This led to the testing of other purified proteins with the result that no purified protein, when fed alone without other food ingredients, could maintain a dog in good health. Despite the lack of knowledge of the essentiality of micronutrients, over a period of a few decades there came a realization that the quality (amino acid composition) of protein in dog diets was important (Chittenden, 1904). In 1905, Kaufmann reported that dogs maintained nitrogen equilibrium when fed a gelatin-based diet supplemented with tyrosine, cystine, and tryptophan. Later work with rats showed that a similar diet was not nutritionally adequate (Jackson et al., 1928). The concentrations of other essential amino acids were too low to meet the requirement of animals for maintenance. Nevertheless, nutritional research with dogs helped establish that certain amino acids present in protein were essential in the diet. Although Abderhalden and coworkers were able to formulate satisfactory diets for dogs using protein hydrolysates during the early part of the twentieth century, they were never successful in formulating a satisfactory diet using amino acids as the sole nitrogen source (Abderhalden et al., 1912). This feat had to wait until Rose isolated and characterized threonine, the last essential amino acid to be discovered that is required by all animals (McCoy et al., 1935). In 1939, Rose and Rice reported a slight positive nitrogen balance in dogs fed amino acid diets containing the same 10 essential amino acids that are required for the growing rat. They also reported that the removal of arginine had no effect on nitrogen equilibrium, whereas later work (Burns et al., 1981) showed that arginine was an essential amino acid for the adult dog. Since Rose and Rice did not publish the composition of the diet they used, the difference between the two studies remains unexplained.

Cats were not used as early or as routinely in nutrition experiments on the essentiality of protein and amino acids as were dogs. One early experiment using cats that had general application was published by Bidder and Schmidt in 1852 in which they showed, using controlled experimental conditions, that after cats ingested all the meat they could eat during a 7-day period, all of the dietary nitrogen (except 0.7 percent, which was within experimental error) was found in feces and urine and none was released as nitrogen gas. Nevertheless, it was not until the middle of the twentieth century that Da Silva and coworkers (1950a,b) and Allison and coworkers (1956) designed satisfactory purified diets that cats would eat readily, and cats could then be used effectively in nutrition research. Not until 1979 were the same 10 amino acids shown to be essential for cats as for dogs and other animal species (Rogers and Morris, 1979).

Structure and Function

With the exception of proline, all amino acids present in most proteins are α-amino acids and have α-amino and α-carboxyl groups, both of which are involved in the peptide bonds that are essential for protein structure. Each amino acid has a side chain on the α-carbon that ranges in size from a hydrogen atom to an indole ring. The various side chains contribute to the secondary and tertiary structure of protein, and several are often conjugated to various other

groups such as phosphate and amino sugars. Also of nutritional importance are the acidic and basic side chains in proteins that can accept or donate protons, depending on the pH of the medium in which the protein is present. Acid-precipitated proteins (e.g., casein) have protons added to the carboxyl group side chains. These protons, together with those on the basic side chains, are released during digestion, absorption, and utilization and contribute to metabolic acidosis. Amino acids are important in providing building blocks for many important biologically active compounds plus countless peptides and proteins. The sensory perception of purified proteins per se is that they are quite bland, whereas peptides and free amino acids have various tastes for humans that range from bitter (e.g., phenylalanine, tryptophan, arginine, leucine), to sour (e.g., glutamic and aspartic acids), sweet (e.g., glycine, threonine), umami (monosodium glutamate), or combinations thereof. The D-amino acids often have a different taste; for example, D-tryptophan is many times sweeter than sucrose. Whether dogs and cats perceive (taste) amino acids in the same way as humans is not known; however selection of amino acids such as leucine by the cat and different neuroresponses by cats and dogs indicate some differences in taste perceptions of different amino acids.

Essentiality of Amino Acids

Dietary protein is required for two reasons. First, protein provides amino acids that dogs and cats cannot synthesize (essential amino acids) but are required for synthesis of the many proteins in the body. Second, protein provides dispensable amino acids (amino acids that can be synthesized if appropriate nitrogen and carbon sources are provided) that animals need for maintenance, growth, gestation, and lactation. Dispensable amino acids provide nitrogen and carbon for the synthesis of any needed dispensable amino acid and carbon for gluconeogenesis and/or energy. Dispensable amino acids also provide nitrogen and/or structural components necessary to make other compounds that are essential for life, such as purines, pyrimidines, heme, various hormones, neurotransmitters, and/or neuromodulators (e.g., thyroxine, catecholamines, γ-aminobutyric acid, taurine). For either dogs or cats that consume primarily animal tissue, amino acids also provide carbon chains for gluconeogenesis to supply glucose to tissues that require it (e.g., red blood cells, nervous tissue) to maintain normal tissue metabolism. As for most other animals, the following 10 amino acids have been shown to be essential for both dogs and cats: arginine (Arg), histidine (His), isoleucine (Ile), leucine (Leu), lysine (Lys), methionine (Met), phenylalanine (Phe), threonine (Thr), tryptophan (Trp), and valine (Val). In omnivores and certain herbivores (e.g., rats, chicks), removal of a single essential amino acid results in a decrease in food intake that is known to be a primary neuroresponse caused by the lack of the limiting essential amino acid (Gietzen, 1993). In cats, the limited work available (e.g., Hardy et al., 1977; Rogers and Morris, 1979) shows that food intake does not decrease as quickly as in rats after initial consumption of a diet devoid of an essential amino acid. Although food intake does decrease with time, the depression is not as severe as in omnivores and herbivores. The depression of food intake appears to be a secondary effect, and the result of a lack of need of energy for growth, since the kittens stop growing and slowly lose weight. Cats may be a good model for strict carnivores since it could be argued teleologically that strict carnivores that eat only animal tissue would never experience an essential amino acid deficiency. Therefore, carnivores do not need to respond in such a sensitive way to a protein or an essential amino acid deficiency as omnivores and herbivores. There is less evidence for dogs. It appears, however, that dogs may respond more like other omnivores (Milner, 1979a,b).

Omnivores and herbivores avoid diets deficient in a single essential amino acid. Rats are able to select between diets that contains less than $0.1 g \cdot kg^{-1}$ difference in an essential amino acid (Hrupka et al., 1997). Hrupka et al. (1999) also showed that the learned taste aversion that mediates this choice against a low dietary concentration of a particular essential amino acid occurs before food intake is decreased. That is, the establishment of a learned taste aversion is more sensitive to a deficiency than simply a reduction of food intake. Little work has been done on whether learned aversions occur after feeding various essential amino acid-deficient diets to dogs and cats. Dogs are known to select for an adequate quantity of protein (three to four times their requirement; Romsos and Ferguson, 1983; Torres et al., 2003), whereas cats do not (Cook et al., 1985).

Digestibility and Bioavailability of Protein and Amino Acids

Digestion of dietary protein by animals involves enzymatic cleavage of the protein to amino acids and small peptide residues that are capable of being absorbed by the mucosal cells of the small intestine. Protein digestibility—or more specifically, total digestive tract digestibility—is generally defined in nutritional science as the percentage of ingested protein that is not excreted in the feces as measured by input and output of nitrogen. Bioavailability is generally defined as the degree to which an ingested nutrient in a particular source is absorbed in a form that can be utilized in the animal's metabolism (Lewis and Bayley, 1995). Much detailed work has been done on the bioavailability of amino acids from common proteins in food-animal nutrition (Lewis and Bayley, 1995; Sibbald, 1987) using ileal digestibilities as a measure of bioavailability. Similar studies have been done with dogs (see Johnson et al., 1998; Bednar et al., 2000; Clapper et al., 2001); however, almost nothing is available for cats (Hendriks and Emmens, 1998; Larsen et al., 2001, 2002), perhaps because of the perceived difficulty in keeping ileally cannulated cats (Mawby et al., 1999).

The first approach in determining bioavailability is to measure "apparent digestibility" of protein in a diet. This provides an overall evaluation of nitrogen absorbed but does not provide a measure of the "quality" or efficiency of utilization of nitrogen or of the individual essential amino acids. Historically, in human and animal nutrition, protein quality tests such as protein efficiency ratio (PER), biological value (BV), and net protein utilization (NPU), as determined in rat assays, have been used as one measure of overall amino acid bioavailability. Net protein utilization provides a measure of the efficiency of utilization of a protein. Differences in efficiencies of utilization of the same protein in various species may result from different digestibilities and/or nitrogen and amino acid requirements. Carnivores in general, including cats, have lower apparent digestibilities of poorly digestible proteins (Kendall et al., 1982; Ahlstrom and Skrede, 1998) and higher requirements for some amino acids such as arginine (Anderson et al., 1979a; Costello et al., 1980). Further refinement of the bioavailability values for individual amino acids results from determination of the ileal digestibility of individual essential amino acids. Although these values provide a better indication of bioavailability than total gastrointestinal (GI) tract digestibility, dietary protein could be 100 percent digested and absorbed, but protein and amino acids would still enter the colon because of gastrointestinal secretions (sloughed mucosa and digestive enzymes). Thus, "true" ileal digestibilities have been measured using a number of techniques to estimate endogenous protein excreted from the ileum (Moughan et al., 1998). Since only some of this endogenous protein is essential for protein utilization, even true digestibilities of nitrogen and essential amino acids may not reflect true bioavailabilities. It should be noted that some dietary proteins contain inhibitors of trypsin or other enzymes that can greatly increase the loss of secreted enzymes. Generally, some in vivo measure, such as weight gain and/or nitrogen retention, is considered the ultimate or "gold standard" for determining nitrogen and amino acid bioavailabilities (Lewis and Bayley, 1995).

The apparent total tract digestibility of protein is similar in rats, cats, and dogs for highly digestible proteins. Proteins with lower digestibilities have higher apparent digestibilities in dogs than in cats (Kendall et al., 1982). For proteins with digestibilities greater than 90 percent (e.g., fresh mince and purified diets), there is no difference in digestibility between dogs and cats. For dry or canned dog or cat foods, dogs have a protein digestibility about 5-8 percent higher than do cats (Kendall et al., 1982). This difference in digestibility of protein in processed foods appears to be the result of the shorter length of the small intestine, relative to body size, in cats compared to dogs. Animal proteins generally have a higher digestibility than do plant proteins (Meyer et al., 1981, 1989; Kendall and Holme, 1982; Neirinck et al., 1991), and prolonged heat processing decreases animal protein digestibility by dogs and cats (Meyer et al., 1981; Backus et. al., 1998; Johnson et al., 1998). Heat processing increases the digestibility of some proteins because antitryptic activity is destroyed by heat (Morgan et al., 1951). The digestibility of protein varies with size, breed, and age of dogs. Pointers had a higher apparent total tract digestibility of protein than huskies (85 vs. 81 percent), and young miniature poodles or schnauzers had a higher digestibility (about 4 percent higher) than did older ones (Hannah et al., 1995). Insoluble fiber is not reported to affect protein digestibility, whereas soluble fiber often decreases the total tract protein digestibility in both dogs (Muir et al., 1996; Silvio et al., 2000) and cats (Sunvold et al., 1995; Harper, 1996).

Digestibilities of the protein in various ingredients of typical dog food by ileally cannulated dogs have shown that the apparent ileal digestibility of crude protein (CP) is about 1-20 percentage units lower than apparent total tract digestibility. Presumably, bacteria degrade and utilize protein in the colon, with the release and absorption of ammonia and other low-molecular-weight nitrogen-containing compounds (Mühlum et al., 1989; Muir et al, 1996; Murray et al., 1997, 1998; Hendriks and $ritharan, 2002). Ileal crude protein digestibilities ranged from 63 to 96 percent whereas total tract protein digestibilities ranged from 71 to 98 percent. When diets contained a high content of low-digestible carbohydrate, ileal apparent protein digestibility was even more impaired than total tract digestibility (Muhlum et al., 1989). Ileal digestibilities of individual amino acids from normal ingredients in dog foods have been shown to vary tremendously (Johnson et al., 1998). True ileal digestibilities for some amino acids such as arginine varied from 77 to 87 percent, whereas others such as cystine, threonine, and lysine varied from 29 to 66 percent, 52 to 78 percent, and 62 to 84 percent, respectively. The lowest amino acid digestibilities were reported for rendered lamb meal, presumably because of extended heating during the rendering and drying process. For all of the essential amino acids, digestibilities of low-ash meat and bone meal were lower (5-18 percentage units) than those of high-ash meat and bone meal. The same was not true for poultry by-product meals for which no difference was found between high- and low-ash meals. Of particular interest is the very low cystine digestibility (29 percent) found in low-ash lamb meal and the finding that, in general, meat and bone meals had higher digestibilities of all of the essential amino acids than did poultry by-product meals. These results indicate the importance of quality control in processing ingredients (i.e., the need to control the rendering and drying processes to preserve a high digestibility of amino acids, especially cystine, threonine, and lysine). Surprisingly, the digestibility of methionine was not as low in this study, varying only from 83 to 93 percent (Johnson et al., 1998). Fiber content of the diet had little effect on ileal digestibility of crude protein except for soluble dietary fibers such as pectin (Meyer et al., 1989; Muir et al., 1996; Silvio et al, 2000). Addition of 50 g pectin·kg^{-1} diet caused a decrease of about 7 percent in ileal,

but only 2 percent in total tract crude protein digestibility (Muir et al., 1996). Good-quality soybean meal (properly heat treated) as an ingredient in dog food has equal or higher ileal and total tract digestibilities than good-quality meat meals (Bednar et al., 2000; Clapper et al., 2001), and the content of various carbohydrates including oligosaccharides in soybean meal had no significant effect on ileal digestibility of soybean protein (Meyer et al., 1989; Zuo et al., 1996). Johnson et al. (1998) compared digestibilities of dog food determined with cecectomized roosters to that with ileally cannulated dogs and found correlation coefficients of 0.89, 0.94, 0.87, and 0.90 for lysine, cystine, threonine, and methionine, respectively. Thus, apparent digestibilities determined by cecectomized roosters may be reasonable approximations for the bioavailabilities of amino acids for dogs.

Larsen et al. (2001, 2002) reported validation of a growth assay to determine bioavailabilities of lysine and methionine in proteins for growing kittens. They showed that weight gain was 25 percent lower when kittens were given a casein diet (moistened, 50 g glucose·kg^{-1} casein, heated at 121°C for 2 hours) than when they were given a diet of non–heat-processed casein. Lysine in the casein before heat treatment had a bioavailability of 96 percent, whereas heat processing with glucose decreased its bioavailability to 56 percent. Since total tract protein digestibilities for the same food are lower in cats than in dogs (Kendall et al., 1982), it is doubtful that the rat or other omnivorous species will be satisfactory as a model for cats (Hendriks and Emmens, 1998).

Assessing Protein and Amino Acid Status

Long-term protein status can be assessed by the maintenance of serum albumin and lean body mass. Examination of concentrations of amino acids in plasma provides a basis for determining which amino acids may be limiting (Zicker and Rogers, 1990) in a particular diet. Acute protein deficiency with adequate intake of energy (e.g., very low protein or protein-free diet) causes a decrease in all amino acids in plasma. In long-term protein deficiency (protein-energy malnutrition), the concentrations of both serum albumin and the essential amino acids (except histidine and phenylalanine) plus tyrosine and cyst(e)ine are much lower than normal, and the dispensable amino acids (especially proline, alanine, serine, and glycine) are higher than normal (Holt et al., 1963). Since changes in concentrations of glycine and valine are most extreme after feeding a very low protein diet, the extent of distortion of the normal glycine:valine ratio has been used as an index of the severity of protein malnutrition. The only known cause of this unique pattern is protein-energy malnutrition. Food deprivation will not produce this pattern but will sustain a more normal amino acid pattern in plasma. If only the glycine:valine ratio is used for a nutritional diagnosis of dogs or cats with kidney disease, a false diagnosis of protein malnutrition may occur. In kidney disease, glycine increases in plasma because the kidney normally converts glycine to serine. However, dogs and cats are often anorexic during renal disease; so, some protein deficiency is not unusual.

Longenecker and Hause (1959) showed that even if dogs were not deficient in protein, the limiting dietary amino acid (and sometimes the second and third limiting) could be determined from the pattern of plasma amino acids. The essential amino acid that decreases the most (or increases the least), as a percentage, after feeding a complete meal containing the protein in question is the one that is most limiting; the one that decreases the next most is second limiting, and so forth. This technique requires overnight food deprivation and the ingestion of a large meal. It is important to note that amino acids tend to return to normal if the animal is food deprived. Alternatively, plasma samples from dogs or cats fed a diet ad libitum for several days and taken in the absorptive phase provide the same information. For example, Hardy et al. (1977) reported that plasma valine decreased markedly when valine was limiting in the diet, from more than 300 nmol·mL^{-1} to 66 nmol·mL^{-1} at the requirement and to 33 nmol·mL^{-1} when valine was left completely out of the diet. Reference data generated in this way are useful to determine whether the need for each essential amino acid has been met. Rogers, Morris, and coworkers have determined the dose-response curve of each essential amino acid during amino acid requirement studies. These data—the concentration of each essential amino acid in plasma after feeding normal diets (adequate intake [AI], i.e, at least 1.5 times the minimum requirement [MR]); the concentration after feeding diets devoid of each essential amino acid (AA); the concentration after feeding diets containing each amino acid just at the MR; and for some amino acids, when present at a great excess (upper limit of tolerance or safe upper limit [SUL]) (Table 6-1)—can be used to determine the essential amino acid adequacy of diets for cats at various life stages. Unfortunately, similar complete plasma amino acid data are not available for dogs. Normal plasma amino acid concentrations are available (Strombeck and Rogers, 1978; Delaney et al., 2003), and some information is available for arginine, leucine, lysine, phenylalanine, and tyrosine for dogs (Tables 6-2A and B).

REQUIREMENTS, ALLOWANCES, AND TOLERANCES OF PROTEIN AND AMINO ACIDS

Role of Metabolic Adaptation in Protein and Amino Acid Nutrition

Relevant to both crude protein and essential amino acid requirements in various species is the nature and extent of metabolic adaptation in nitrogen and amino acid metabolism. For example, rats can down-regulate nitrogen catabolic enzymes to such an extent that they maintain nitrogen balance when fed a diet containing 4-5 percent of metabolizable energy (ME) as protein (National Research Council,

TABLE 6-1 Plasma Amino Acid Concentrations ($nmol \cdot mL^{-1}$) of Kittens

Amino Acid	–AA[a]	MR[b]	AI[c]	SUL[d]
Arginine	28	75	100	400
Histidine	9	55	100	>200
Isoleucine	8	30	75	>3,000
Leucine	25	75	125	>1,600
Lysine	45	60	110	>600
Methionine	11	30 (70)[e]	45	400
Phenylalanine	11	25 (75)[f]	65	>900
Tyrosine	10	35	50	310
Threonine	60	80	150	>1,400
Tryptophan	9	25	50	130
Valine	33	66	130	>6,000
Glutamate	50-100	—	50-100	200

[a]Amino acid concentration from kittens fed, in turn, diets lacking each amino acid.
[b]Amino acid concentration from kittens fed, in turn, diets containing each amino acid at the minimum requirement.
[c]Amino acid concentration from kittens fed, in turn, diets containing each amino acid at 150% or more of the requirement (i.e., adequate intake).
[d]Amino acid concentration from kittens fed, in turn, diets containing each amino acid at great excess, at or below the SUL.
[e]70, without any cystine in the diet.
[f]75, without any tyrosine in the diet.
SOURCE: Summarized from Zicker and Rogers (1990) and Taylor et al. (1996, 1998).

1995). Rats can also down-regulate the lysine catabolic pathway such that the lysine requirement for maintenance is only 12 percent that for growth, whereas the lack of specific down-regulation of isoleucine degradative enzymes results in an isoleucine requirement for maintenance 50 percent that for growth. The same detailed information is not available

TABLE 6-2A Plasma Amino Acid Concentrations ($nmol \cdot mL^{-1}$) of Puppies

Amino Acid	–AA[a]	MR[b]	AI[c]	SUL[d]
Arginine	25	72	135	—
Leucine	18	100	150	—
Lysine	30	85	190	—
Phenylalanine	30[e]	85[e]	60[f]	—
Tyrosine	4[e,g]	12[g]	50[f]	—

[a]Amino acid concentration from puppies fed, in turn, diets lacking each amino acid.
[b]Amino acid concentration from puppies fed, in turn, diets containing each amino acid at the minimum requirement.
[c]Amino acid concentration from puppies fed, in turn, diets containing each amino acid at 150% or more of the requirement (i.e., adequate intake).
[d]Amino acid concentration from puppies fed, in turn, diets containing each amino acid at great excess, at or below the SUL.
[e]Concentration of phenylalanine when tyrosine is not present in the diet.
[f]Concentration of phenylalanine and tyrosine when both are present in the diet.
[g]Concentration of tyrosine when it is not present in the diet.
SOURCE: Summarized from the work of Strombeck and Rogers (1978); Czarnecki and Baker (1984); Milner et al. (1984); Czarnecki et al. (1985); Hirakawa et al. (1986); Delaney et al. (2001).

TABLE 6-2B Plasma Amino Acids Concentrations ($nmol \cdot mL^{-1}$) from Normal, Small-, and Large-Breed Adult Dogs ($n = 131$) Fed a Variety of Commercial Diets Known to Be Adequate for Maintenance

Amino Acid	Mean	SEM
Alanine	388	9.6
Arginine	102	2.6
Asparagine	40	1.1
Aspartate	7	0.2
Citrulline	41	1.9
Cysteine	46	1.3
Glutamate	23	1.2
Glutamine	495	9.4
Glycine	268	8.4
Histidine	71	1.6
Hydroxyproline	67	4.1
Isoleucine	51	1.3
Leucine	120	3.2
Lysine	132	5.0
Methionine	57	1.6
Ornithine	35	1.5
Phenylalanine	45	0.9
Proline	246	8.2
Serine	107	2.6
Taurine	77	2.1
Whole blood	266	5.1
Threonine	178	5.0
Tryptophan	60	1.7
Tyrosine	39	1.1
Valine	157	4.1

NOTE: SEM = standard error of the mean.
SOURCE: Delaney et al. (2003).

for dogs or cats; however, it is known that neither is as efficient in down-regulating nitrogen catabolic enzymes as rats (Rogers et al., 1977; Morris et al., 2002). Herbivores and omnivores in general show up- and down-regulation of nitrogen catabolic enzymes and of enzymes involved in the first irreversible step in the catabolism of essential amino acids. For the disposal and conservation of nitrogen, these adaptations particularly involve the up- and down-regulation of all of the urea cycle enzymes (Schimke, 1962), as well as alanine aminotransferase and aspartic aminotransferase (Kaplan and Pitot, 1970). Changes in the flux through the urea cycle occur without a change in the amount of enzymes as a result of the following:

1. **Increasing or decreasing the concentration of substrate**. Increasing or decreasing the concentration of alanine, aspartic acid, ammonia, and glutamic acid will affect the flow of nitrogen from these and other amino acids into urea since most of the catabolic enzymes are working with substrate concentrations considerably below their Michaelis constant (K_m) values.

2. **Changes in the concentration of ornithine in the liver**. As the postabsorptive state approaches and ammonia coming from the amino acids decreases or after feeding a

low-protein diet, ornithine concentration in the liver decreases (as a result of the activity of ornithine δ-aminotransferase) and with very little acceptor available for carbamoyl phosphate, urea synthesis markedly decreases. After ingestion and absorption of arginine (usually in dietary protein) and the action of liver arginase, the liver is provided with sufficient ornithine to maximize urea synthesis for any particular activity of the urea cycle enzymes. If ornithine is limiting in the liver and a nitrogen source free of or low in arginine is given to an animal (Wergedal and Harper, 1964), hyperammonemia occurs. Cats (Morris and Rogers, 1978a,b) are more sensitive to arginine deficiency than dogs (Burns et al., 1981; Czarnecki and Baker, 1984), which, in turn, are more sensitive than rats (Milner et al., 1975; Rogers, 1994).

3. **Allosteric regulation of carbamoyl phosphate synthase.** The first step in the synthesis of urea occurs via activation by *N*-acetylglutamate (NAG). Synthesis of NAG is allosterically regulated by arginine. Thus, although the K_a of NAG synthesis for arginine is five times higher in cats than in rats, the concentration of arginine in liver, as well as the precursors of NAG (glutamate and acetyl coenzyme A), influence hepatic NAG concentrations (Stewart et al., 1981). Both arginine and glutamate increase rapidly in liver after the intake of a high-protein meal, enhancing the ability of the liver to dispose of excess nitrogen. As substrates for urea synthesis decrease, NAG diffuses out of the mitochondria and is cleaved by an acetylase.

4. **Up- and down-regulation of the nitrogen catabolic enzymes.** The final level of control to enable the animal to maintain amino acid homeostasis is the up- and down-regulation of the nitrogen catabolic enzymes. This regulation can occur by changing the rate of degradation of the enzymes or, more generally, by changing the rate of synthesis of the enzymes through increasing the rate of synthesis of mRNA. Up- and down-regulation of the nitrogen catabolic enzymes does not appear to occur to any great extent in the cat (Rogers et al., 1977; Tews et al., 1984) and occurs to a lesser extent in the dog (Morris et al., 2002) than in the rat. The three levels of control mentioned above are all rapid, occurring in seconds, whereas the changes in the amounts of the enzymes take 1-5 days. It appears that the extent to which animals can up- and down-regulate the amounts of the nitrogen catabolic enzymes is what really dictates the ability, on the one hand, to efficiently utilize high-protein diets, and, on the other, to be able to maintain nitrogen balance when fed a low-protein diet. Thus, it has been suggested that the high-protein requirement of adult cats at maintenance is the result of the inability to effectively down-regulate the hepatic nitrogen catabolic enzymes (Rogers et al., 1977). This interpretation has been challenged by Russell et al. (2002) using respiration calorimetry to measure protein oxidation in adult cats; they showed that cats fully oxidized all of the protein after adaptation to a normal (350 $g \cdot kg^{-1}$) and a high (520 $g \cdot kg^{-1}$) crude protein diet. These authors suggest that it is still unknown how the cats adapted to these two levels of protein, whereas Rogers and Morris (2002) contend that the first three levels of control described above, together with an increase in liver size (thereby increasing the total hepatic nitrogen catabolic enzymes), are sufficient to provide for complete oxidation of the relatively high quantities of dietary protein tested. Russell et al. (2002) did not address the inability of the cat to adapt to low-protein diets. Regardless of the interpretation of the results of these two groups, studies of the requirement for maintenance of adult cats show the lack of ability of cats to maintain nitrogen balance at the same minimal dietary concentration as dogs and the inability of dogs (at least long term) to maintain nitrogen balance at the same low concentration as that of rats.

The limited information available on the effect of dietary protein on amino acid metabolism (Primal et al., 1986; Humbert et al., 2002) and the adaptation of enzymes involved in the first step of the degradation of the essential amino acids (as well as important dispensable amino acids such as tyrosine and cystine) indicate some up- and down-regulation of these enzymes in the cat, but not to the same extent as in rats. For enzymes involved in the metabolism of tryptophan (Leklem et al., 1969), histidine (Rogers et al., 1977), methionine (Fau et al., 1987a; Strieker, 1991), threonine (Hammer et al., 1996b), tyrosine (Bai et al., 1998), cysteine (Park et al., 1999), and taurine transport (Park et al., 1989), only about a 20-120 percent increase in activity occurs in cats switched from a low- to a high-protein diet, compared to a severalfold increase of these enzymes in rats. For example, threonine catabolic enzymes increase only about twofold when cats are switched from a low- to a high-protein diet (Hammer et al., 1996b), whereas under similar conditions, better than a tenfold increase occurs in rats (Freedland and Avery, 1964; Harper, 1968). Likewise, diet-induced daily rhythms as a result of eating a normal diet cause only a slight change (about 35 percent) in hepatic tyrosine aminotransferase activity of cats (Bai et al., 1998), whereas in rats a four- to five-fold change occurs (Wurtman and Axelrod, 1967). The consequence of less metabolic adaptation in dogs and cats is that even after adapting to a high-protein diet, plasma amino acid concentrations are higher after a meal (Tews et al., 1984; Torres and Rogers, 2002), whereas in rats after adaptation, plasma amino acids are similar whether they are adapted to a low- or a high-protein diet (Anderson et al., 1968).

Nitrogen (Crude Protein) Minimum Requirements, Recommended Allowances, and Adequate Intakes

Variables Used in Assessing Protein and Amino Acid Requirements

Nitrogen Balance

Nitrogen balance has, for many decades, been the preferred dependent variable for determining nitrogen and

amino acid requirements for all life stages. Often, there is no difference in the breakpoints for weight gain or nitrogen retention to determine individual amino acid requirements for growth of many species. Nevertheless, there are situations (and certain requirements) in which for dogs and cats, the breakpoint for nitrogen balance results in a higher requirement than that for weight gain. However, in determination of the nitrogen requirement of cats, a clear plateau does not always occur (Hammer et al., 1996a), but, after the breakpoint, there is still a significant positive slope. Although maximal nitrogen retention has been the standard variable used, when determining the nitrogen requirement, it has been shown that apparent nitrogen balance for maintenance may be sustained while lean body mass is decreasing, apparently because of the low sensitivity and consistent errors in a positive direction for nitrogen retention that do not exist for the usual determinations of lean body mass (Hannah and Laflamme, 1996). In some experiments, only weight gain has been used; in others, both weight gain and nitrogen balance or just nitrogen balance (e.g., for maintenance). In still others, some other metabolic or physiological variable was used. In reviewing the literature on nitrogen and amino acid requirements, the variable that resulted in the highest MR was used.

Growth

The crude protein requirements for growing puppies and kittens have been determined primarily by using weight gain and nitrogen balance as the dependent variable. Mixed-food proteins have been used in practical diets, and purified proteins or free amino acids have been used in purified diets. Many experiments were done before the individual essential amino acid requirements were known for either of these species. There do not appear to be any detrimental effects (except a slightly lower growth rate) of feeding diets at or slightly below the nitrogen requirement, provided all of the essential amino acid requirements are met for all functions known besides growth of muscle tissue and other structural body proteins (e.g., sufficient arginine for optimal urea cycle function, sufficient histidine to prevent cataracts). Under these conditions, if energy intake is restricted along with protein, there may be an increase in longevity in some breeds of dogs due to a delay in onset of chronic diseases (e.g., arthritis and insulin resistance) (Kealy et al., 2002).

Maintenance, Gestation, and Lactation

Satisfactory maintenance can be achieved using a wide variety of dietary crude protein concentrations for adult cats on purified diets and diets using common feed ingredients. Cats, as compared to dogs, rats, and many herbivores or omnivores, do not show effective adaptation to low-protein diets and, thus, excrete considerably more nitrogen when fed a protein-free diet (Hendricks et al., 1997) or when food deprived (Biourge et al., 1994). A comparison of obligatory nitrogen excretion in various species is shown in Table 6-3. It is apparent that the obligatory nitrogen loss in cats is similar whether adult cats were fed a protein-free diet or were food deprived, the loss being nearly twice that of dogs, while the loss in dogs is more than three times that of humans. These data support the fact that cats have a higher nitrogen requirement than these other species. The efficiency of utilization (e.g., NPU; Jansen et al., 1975) of protein for maintenance and growth is also lower in cats than in these other species. This appears to be the result of lack of ability to conserve both nitrogen and essential amino acids even though, on a relative basis, the nitrogen requirement is higher than that for the essential amino acids.

The protein requirements for reproduction of dogs or cats have not been studied extensively and, therefore, have not been well defined. General observations in both species indicate that the crude protein requirement and amino acid requirements for gestation do not exceed those found for maximal nitrogen retention of weanling puppies or kittens, whereas the requirement for maximal lactation is known to exceed that for maximal weight gain of weanling puppies and kittens.

Application of Variables to Assess Requirements

The most common variables found in reviewing the literature for crude protein and amino acid requirements of dogs and cats at various life stages were weight gain for growing animals and nitrogen balance for adult animals. In this section, the variables that result in the maximum requirement are used. Most often, a metabolic variable, such as minimizing urinary orotic acid for the arginine requirement or maximizing blood hemoglobin for the histidine requirement, gave the highest value. Often data on response to variable dietary concentrations were not available, especially for maintenance, gestation, and lactation. Therefore, for each amino acid, an adequate intake (AI) was estimated for the life stage from the quantity of each amino acid in the digestible protein of commercial, dry diets that were known to support normal maintenance, growth, and reproduction. Successful growth and reproduction of dogs and cats fed

TABLE 6-3 Endogenous Urinary Nitrogen Excretion of Animals Fed a Protein-Free Diet

Animal	mg $N \cdot kg^{-0.75} \cdot d^{-1}$
Human	62
Marmoset	110
Rat	128
Pig	163
Dog	210
Cat	360

SOURCE: Taken from Hendriks et al. (1997).

such diets over a period of several years are common. When requirement data were not available, these estimated AIs were also used as the recommended allowances.

Growth

Dogs

Estimates of the nitrogen requirement of growing puppies go back many decades. Summaries in the National Research Council (NRC) Nutrient Requirements series for dogs for crude protein, as a percentage of energy, in 1953, 1962, 1972-1974, and 1985 were, respectively, 200, 220, 220, and ~95-115 g·kg^{-1} diet. There is general consistency in the recommended crude protein requirement across the decades except the 1985, which is the sum of the amino acids suggested (including the dispensable amino acids). It becomes apparent from the review by the 1985 NRC committee and from reviewing the literature over the past 20 years that there is a marked decrease in the requirements for both nitrogen and essential amino acids between about 10 and 14 weeks of age for growing puppies; thus, different requirements for weanling puppies before and after 14 weeks of age are suggested. Also, in some instances, weight gain, rather than nitrogen balance, has been used as the variable to determine the requirement. For dogs, generally more dietary crude protein is required for maximal nitrogen retention than for maximal weight gain. For newly weaned small-breed or large-breed puppies, when near maximal weight gains were obtained, the MR appears to be a 180-g CP·kg^{-1} diet containing 4.0 kcal ME·g^{-1} (Milner, 1981; Burns et al., 1982; Nap et al., 1993; Schaeffer et al., 1989; Delaney et al., 2001). These studies used either highly digestible protein or free amino acid diets, and all of the known essential amino acid requirements were met for maximal nitrogen retention. When practical diets from cereals and various animal by-products are used, the crude protein needed for maximal nitrogen retention (AI) appears to be about 250 g·kg^{-1} diet (Ontko et al., 1957; Case and Czarnecki-Maulden, 1990). For puppies over 14 weeks of age, the respective crude protein requirements (MR) for purified highly digestible diets and practical diets (AI) are, respectively, 140 and 200 g·kg $^{-1}$diet containing 4.0 kcal ME·g^{-1} (Gessert and Phillips, 1956; Burns et al., 1982; Delaney et al., 2001).

Cats

Several estimates have been made of the nitrogen requirement of growing kittens. The earliest estimates, determined without considering the essential amino acid requirements, were about 250-350 g of dietary crude protein per kilogram of diet (Dickinson and Scott, 1956; Miller and Allison, 1958; Greaves, 1965; Jansen et al., 1975). More recent estimates, based on dose-response curves in which protein or amino acid diets were used that contained all of the essential amino acids at least 50 percent above the requirements as listed by the NRC (1986), reported crude protein requirements in the range of 160-240 g·kg^{-1} diet containing 4 kcal ME·g^{-1} (Anderson et al., 1980a; Smalley et al., 1985; Rogers et al., 1987). In a series of papers, Taylor and coworkers (1996, 1997, 1998; Rogers et al., 1998) examined the pattern of amino acids required for maximal weight gain and nitrogen retention by growing kittens, varying both the concentration of crude protein in the diet and the ratio of essential amino acid nitrogen to total amino acid nitrogen (E:T). At or below the essential dietary amino acid requirements, the addition of crude protein (as dispensable amino acids) caused a decrease in weight gain and nitrogen retention that was corrected by additional arginine supplementation. If methionine and arginine were restricted to not more than about twice their requirements, optimal weight gains and nitrogen retention were observed, with all of the nitrogen coming from essential amino acids plus cystine and tyrosine. Kittens, therefore, can grow maximally (see Figure 6-1) with a much broader E:T ratio (Rogers et al., 1998; Taylor et al., 1998) than rats (Stucki and Harper, 1962) or chicks (Stucki and Harper, 1961). This work, using free amino acid diets and diets containing purified proteins (Smalley et al., 1985; Schaffer et al., 1989), indicates the minimum crude protein requirement (MR) for growth (with essential amino acids at about 150 percent of the 1986 NRC requirements) is about 180 g CP·kg^{-1} diet containing 4.0 kcal ME·g^{-1}. The E:T ratio may vary widely at intermediate crude protein concentrations; however, the ratio has to be higher for similar weight gains at both low and high dietary crude protein concentrations (Figure 6-1). The E:T ratio must be high for low dietary crude protein concentrations in

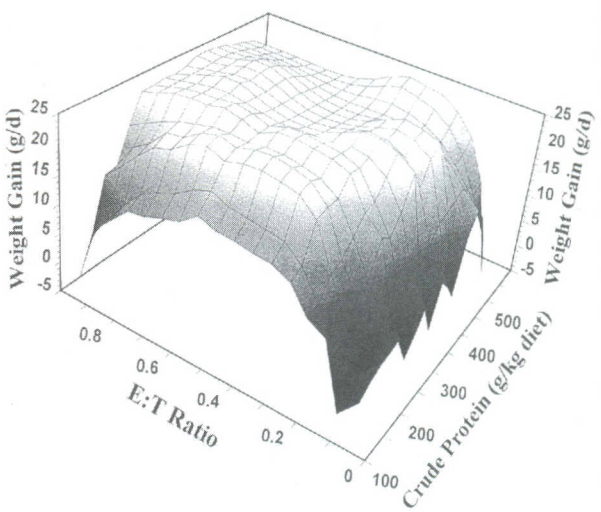

FIGURE 6-1 Effect of dietary crude protein and ratio of essential amino acid nitrogen to total amino acid nitrogen (E:T) on weight gain of kittens. SOURCE: Taken with permission from Rogers et al., 1998.

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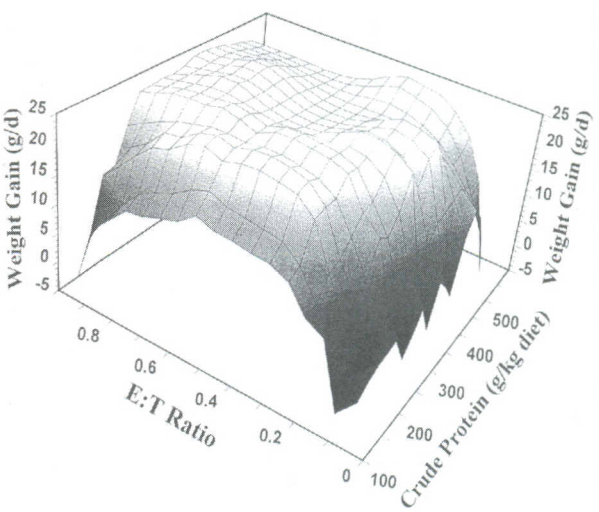

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order to provide all of the necessary essential amino acids (Taylor et al., 1997) and high at very high dietary crude protein concentrations to prevent toxicity of some dispensable amino acids such as glutamate. Glutamate is considerably more toxic when other dispensable amino acids are also high in the diet, presumably because metabolic equilibrium results in higher plasma and tissue glutamate concentrations (Taylor et al., 1998). Thus, for both low and high dietary protein concentrations, body weight gains are higher with high-quality than with low-quality proteins. Protein quality is less important at intermediate protein concentrations in the diet. In evaluating commercial, dry expanded diets that have sustained normal growth for growing kittens, none contained less than 280 g CP·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Maintenance

Dogs

Early estimates of the MR for crude protein for adult dogs at maintenance, using nitrogen balance as the criterion, varied from about 35 to 90 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1} for good-quality proteins. These values came from experiments using food proteins without knowledge of the amino acid requirements for either growth or maintenance (Melnick and Cowgill, 1937; Kade et al., 1948; Arnold and Schad, 1954; Wannemacher and McCoy, 1966). Recently, Sanderson et al. (2001) published a study in which beagles maintained body weight (BW) and sustained normal blood chemistries and health (except for one dog that developed dilated cardiomyopathy, which was corrected by taurine supplementation) for 42-48 months with a diet calculated to be 82 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1} as a highly digestible, high-quality protein. Except for the question about meeting the taurine need of the dogs, these results together with earlier work suggest 80 g of crude protein per kilogram of diet containing 4.0 kcal ME·g^{-1} as the MR. Other studies (Wannemacher and McCoy, 1966; Ward, 1976), published and unpublished, support an AI of about 100 g·kg^{-1} diet containing 4 kcal ME·g^{-1} as being adequate, thus suggesting 100 g CP·kg^{-1} diet as the RA. Older dogs appear to require somewhat more crude protein to maintain labile protein (so-called protein reserves), perhaps as much as 50 percent more (Wannemacher and McCoy, 1966). The optimal concentrations for other variables and outcomes (e.g., optimal immune response, wound healing, health in old age) have to be evaluated before more specific recommendations can be made.

Cats

Early estimates of the minimum crude protein requirement (or allowance) (MR) of adult cats for maintenance, using nitrogen balance as the criterion, varied from about 10 to 30 percent of ME. These values came from experiments using food proteins without knowledge of the amino acid requirements for either growth or maintenance (Allison et al., 1956; Miller and Allison, 1958; Greaves and Scott, 1960) or sometimes without considering the digestibility of the dietary proteins. The difficulty in making a purified diet readily acceptable to adult cats, (often very choosy about the texture and taste of their food), has made determining the crude protein and amino acid requirements problematical. Indeed, in one of the most thorough, long-term studies reported, using nitrogen balance as the criterion in which the diet contained the essential amino acids at a dietary concentration at least equivalent to the essential amino acid requirements of the growing kitten, the crude protein requirement was suggested to be 125 g·kg^{-1} diet (100 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}) (Burger et al., 1984; Burger and Smith, 1987). However, the authors removed some cats from the study because they would not accept the diet, and the cats as a whole lost a small amount of weight. Nitrogen balance is known to underestimate the nitrogen requirement because of incomplete collection of feces and spilled food. In most experiments with most species, there is a plateau at a small positive nitrogen balance. In the work of Burger et al. (1984), when the regression line crossed at 0 nitrogen balance, 7 of 18 cats fed 164 g CP·kg^{-1} diet were in negative nitrogen balance. With all but one cat in positive nitrogen balance, the protein intake was calculated to be about 160 g·kg^{-1} diet containing 4 kcal ME·g^{-1}. This value is taken as the crude protein MR of adult cats for maintenance. It should be pointed out that other outcome variables such as optimizing immune response, labile tissue protein, or environmental stress were not considered in this MR. If a safety allowance is made for such needs, a recommended allowance (RA) of 200 g CP·kg^{-1} diet containing 4 kcal ME·g^{-1} is suggested. In evaluating commercial, dry, expanded diets that have sustained maintenance for months to years, none were found with less than 265 g CP·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Gestation and Lactation

Dogs

The protein and amino acid requirements of dogs during reproduction have not been well defined. In general, it has been assumed that, if the dietary crude protein requirement is met for growing puppies, the diet would meet the crude protein requirement of bitches during gestation and lactation. No reports could be found in which the crude protein requirement for gestation or lactation had been determined using dose-response relationships in bitches fed purified diets. From experimental work using natural ingredients (Visek et al., 1976) and evaluating commercial, dry dog foods that have routinely supported normal gestation and lactation, the AI for crude protein for gestation and lactation for the bitch has been shown to be 180-210 g·kg^{-1} diet containing 4 kcal ME·g^{-1}. Meyer et al. (1985) did a factorial cal-

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Dogs

The protein and amino acid requirements of dogs during reproduction have not been well defined. In general, it has been assumed that, if the dietary crude protein requirement is met for growing puppies, the diet would meet the crude protein requirement of bitches during gestation and lactation. No reports could be found in which the crude protein requirement for gestation or lactation had been determined using dose-response relationships in bitches fed purified diets. From experimental work using natural ingredients (Visek et al., 1976) and evaluating commercial, dry dog foods that have routinely supported normal gestation and lactation, the AI for crude protein for gestation and lactation for the bitch has been shown to be 180-210 g·kg^{-1} diet containing 4 kcal ME·g^{-1}. Meyer et al. (1985) did a factorial cal-

culation based on experimental work on milk yield and milk composition of bitches and recommended 210 g CP·kg^{-1} diet containing 4 kcal ME·g^{-1}, provided the protein quality was good and the diet contained carbohydrates. Based on their experimental work, they also calculated values of 10 g protein·kg BW$^{-0.75}$ for small bitches suckling two puppies, 20 g·kg BW$^{-0.75}$ for medium-sized bitches suckling six puppies, and 25 g·kg BW$^{-0.75}$ for large bitches suckling eight puppies. Romsos et al. (1981) evaluated reproduction with and without dietary carbohydrate using diets containing about 260g·kg^{-1} crude protein (180-210 g digestible crude protein·kg^{-1} at 4 kcal ME· g^{-1}) and showed that this concentration was ample protein for both gestation and lactation if the diet contained carbohydrate, whereas, if the diet contained no carbohydrate, 260 g CP·kg^{-1} diet was insufficient for the latter part of gestation but was sufficient for lactation. Kienzle et al. (1985) showed that, when carbohydrate-free diets were fed to pregnant and lactating bitches, a protein content of 400 g·kg^{-1} diet was sufficient for successful reproduction, but a protein content of only 200 g·kg^{-1} diet led to severe impairment of reproduction including hypoglycemia in the bitches, high losses of puppies, low liver glycogen in the puppies, increased milk fat, decreased milk lactose and water content, and decreased milk yield. From the above results, the AI/RA for highly digestible crude protein for gestation and lactation is set at 200 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}, provided there is carbohydrate in the diet.

Cats

The protein and amino acid requirements of queens during reproduction have not been well defined. It has been assumed that the dietary crude protein requirement for the growing kitten would meet the crude protein requirement of the queen during gestation and lactation. Factorial calculations by Kienzle (1998) of the protein requirements of queens during peak lactation indicated that 210-290 g·kg^{-1} diet containing 4 kcal ME·g^{-1} was required. Piechota et al. (1995), using purified diets based on soybean protein-casein (supplemented with essential amino acids to bring each one to at least 150 percent of the 1986 NRC requirements for growth), reported the MR to be not greater than 170 g·kg^{-1} diet containing 4 kcal ME·g^{-1} for gestation and about 240 g·kg^{-1} for lactation using kitten weight gain and queen weight loss during lactation as key variables. Thus, the MRs for crude protein for cats during gestation and lactation, respectively, are taken as 170 and 240 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}. This requirement for lactation is consistent with the lowest level of digestible crude protein found in a number of dry, expanded, commercial diets that have regularly sustained gestation and lactation. From an evaluation of plasma amino acid results, the highest nutritional requirement appeared to be during peak lactation (third to fourth week), before the kitten's intake of the queen's diet was significant. When plasma amino acids were used as the criterion, several essential amino acids appeared to be near limiting, even with commercial diets containing 260 g·kg^{-1} crude protein (4 kcal ME·g^{-1}). Methionine appeared to be the limiting amino acid most often, with the crude protein and amino acid requirements being higher for maximal lactation than for maximal growth of kittens.

Amino Acid Minimum Requirements, Recommended Allowances, Adequate Intakes, and Safe Upper Limits

Satisfactory maintenance and maximal growth and reproduction of dogs and cats can be achieved on a wide variety of concentrations of amino acids in purified diets using either free amino acids, amino acids in purified proteins, or proteins from common feed ingredient incorporated into dry expanded or canned diets; that is, no upper limit is known. The 10 amino acids shown to be essential for growing rats have been shown to be essential for growing dogs and cats. No studies have been reported in which the essential amino acids for other life stages have been deleted from the diet of either dogs or cats, except for the abstract of Rose and Rice (1939), which showed that all of the same amino acids that are essential for adult rats are essential for adult dogs. Later, Burns et al. (1981) reported that arginine was essential in the diet to prevent hyperammonemia and orotic aciduria in the adult dog. Similar to other adult species, it is assumed all of the other amino acids essential for adult rats and humans are essential for adult dogs and cats.

Arginine

Some synthesis of arginine occurs in many mammals and at a sufficient rate to provide all of the arginine needs for a variety of species including humans, ruminants, and adult rats and swine (Rogers, 1994). Metabolically, arginine is glucogenic and has functions other than its role in the synthesis of innumerable proteins. Arginine is an intermediate in the urea cycle, and when absorbed with a meal, it acts both anaplerotically to stimulate urea synthesis and as an allosteric activator of acetylglutamate, which in turn, is an essential allosteric activator of carbamoyl-phosphate synthase, the first enzyme in the detoxification of ammonia and the synthesis of urea. In addition, arginine has been shown to elicit the release of several hormones and metabolic mediators including insulin, glucagon, and gastrin, and it is a precursor of biogenic amines, which are important in cell replication. Arginine is also the precursor of nitric oxide, the neurotransmitter involved in many systems, from its effect on blood pressure via relaxation of blood vessels to its role in macrophages in killing foreign cells (e.g., bacteria and viruses). There have been many studies using arginine as a therapeutic agent, apart from its role in normal nutrition and health. The committee's recommendations are based on the need of dogs and cats to minimize urinary orotic acid.

Dog

Signs of Deficiency

When Labrador retrievers, beagle puppies (Ha et al., 1978), or English pointer puppies (Czarnecki and Baker, 1984) were given an arginine-free diet containing about 140 g of crude protein per kilogram, a decrease in food intake occurred together with severe emesis, associated with hyperammonemia, but no muscle tremors or excessive salivation were observed. Excessive salivation and muscle tremors occurred when the dietary crude protein in the arginine-free diet was increased to 280 $g \cdot kg^{-1}$ (Ha et al., 1978). Elevated urinary orotic acid excretion occurred at all levels of dietary crude protein in puppies fed arginine-free diets. Czarnecki and Baker (1984) also showed that older dogs (20 weeks old) performed no better than recently weaned puppies on arginine-free diets. Emesis occurred at peak ammonia concentrations. At a concentration of citrulline or ornithine equimolar to that of 4 $g \cdot kg^{-1}$ of dietary arginine (their suggested requirement for arginine to sustain maximal growth), some orotic aciduria occurred and clinical signs of arginine deficiency were present but were less severe. Citrulline could replace arginine for growth but more was required, and ornithine did not support growth of puppies fed an arginine-free diet. Adult pointers also have been shown to require dietary arginine to prevent orotic aciduria (Burns et al., 1981). When dogs were force-fed the arginine-free diet, clinical signs became more severe and included frothing at the mouth and muscle tremors. In these short-term experiments and in those of Rose and Rice (1939), nitrogen balance was maintained in adult dogs fed the arginine-free diets. It is clear that dogs are more sensitive to an arginine deficiency that rats but not as sensitive as cats.

Vainisi et al. (1981) reported cataracts in wolf pups greater than 3 weeks old that were fed a milk-replacer diet from 7 to 10 days of age. Cataracts were prevented by either arginine or lactose supplementation or by fostering the pups onto another lactating wolf or dog. Cataracts assumed to be a result of arginine deficiency have also been reported in large-breed puppies fed a milk-replacer diet (Glaze and Blanchard, 1983; Martin and Chambreau, 1982; Ranz et al., 2002). Clearly the arginine, and indeed all of the essential amino acids, were low in the diet, but the mechanism whereby additional arginine or lactose would prevent cataracts has not been reported. It may be mediated by some common secretagogue effect, such as increased secretion of insulin. These results, together with metabolic information available on the utilization of other nutrients such as niacin, vitamin D, and taurine, suggest that metabolically dogs have more carnivorous nutritional metabolic characteristics than rats but less than cats.

Requirements and Allowances

The requirement of arginine for maximal growth has been shown to be about 4-5.6 $g \cdot kg^{-1}$ diet for growing Labradors (Ha et al., 1978) and pointers (Czarnecki and Baker, 1984) for a diet containing about 4.2 kcal $ME \cdot g^{-1}$. The only published arginine-response experiments with puppies indicate that the quantity of arginine necessary to prevent orotic aciduria (extrapolated at breakpoint) was 5.3 $g \cdot kg^{-1}$ diet containing about 140 g of crude protein per kilogram and 4.2 kcal $ME \cdot g^{-1}$ (Czarnecki and Baker, 1984). By making an adjustment to 4.0 kcal $ME \cdot g^{-1}$ and a possible increase in the requirement if 180 g of crude protein was used per kilogram of diet, MRs of 6.3 $g \cdot kg^{-1}$ diet for puppies 4-14 weeks of age and 5.3 $g \cdot kg^{-1}$ diet for puppies over 14 weeks of age are suggested. Since both of the above groups have shown that increasing dietary nitrogen increases the severity of clinical signs when a low-arginine or arginine-free diet is fed, it is recommended that 0.01 g arginine be added for each gram of crude protein above the requirement. The concentration in routine commercial, dry, expanded diets and various purified diets with which normal, sustained growth has routinely been observed is about twice the above values.

Adverse Effects of Excess Consumption

No reports could be found on acute or chronic toxicity related to feeding excess free arginine in the diet of dogs in the range of arginine toxicity in rats. Thus, no SUL can be established at this time.

Cat

Signs of Deficiency

When cats that were given an arginine-free diet that contained substantial quantities of other amino acids were deprived of food overnight, severe hyperammonemia occurred within 1-3 hours that resulted in vocalization, emesis, ptyalism, hyperactivity, hyperesthesia, ataxia, tetanic spasms, emprosthotonus, extended limbs with exposed claws, apnea, cyanosis, and depending on the amino acid load ingested, death (Morris and Rogers, 1978a). Under free-feeding conditions of an arginine-free diet, clinical signs were less severe but included diarrhea, severe weight loss, learned taste aversion, and refusal of the diet (Morris and Rogers, 1978b). Addition of ornithine or citrulline (Morris et al., 1979) to the arginine-free diet prevented hyperammonemia and clinical signs; however, growth was restored only with citrulline—and not with ornithine—added to the diet that lacked arginine. These observations indicate that both ornithine and citrulline acted anaplerotically in the urea cycle to stimulate urea synthesis, but neither ornithine nor citrulline can be made at a fast enough rate in vivo; the precursors needed for synthesis of arginine, which is needed for growth and optimal urea synthesis, function in the intestine (Rogers, 1994). However, exogenous citrulline could be converted to arginine at a sufficient rate in the kidney to sustain maximal growth

and provide for satisfactory urea synthesis. The metabolic basis for the strict essentiality of arginine in the cat is the very low enzymatic activity of both pyrroline-5-carboxylate synthase (Rogers and Phang, 1985) and ornithine δ-aminotransferase (Morris, 1985) in the small intestine where ornithine and citrulline are made before citrulline goes to the kidney to be converted to arginine (Levillain et al., 1996). Other carnivores and some herbivores and omnivores have an absolute requirement for arginine for optimal growth (Rogers, 1994), but none have yet been shown to be as sensitive to arginine-deficiency hyperammonemia as cats, perhaps because the cat is the most strict carnivore studied in such depth.

Requirements and Allowances

The requirement of arginine for maximal growth of the weanling kitten has been shown to be about 8-8.3 $g \cdot kg^{-1}$ diet (Anderson et al., 1979a; Costello et al., 1980) when the diet contains about 4.7 kcal $ME \cdot g^{-1}$. However, to minimize urinary orotic aciduria (Costello et al., 1980), about 10.5 g arginine$\cdot kg^{-1}$ diet containing about 280 g $CP \cdot kg^{-1}$ diet is required. Taylor et al. (1997) showed that increasing the total nitrogen content of the diet increased the quantity of arginine necessary to prevent increased orotic acid excretion above baseline. For a diet containing 155 g of crude protein per kilogram of diet (4.0 kcal $ME \cdot g^{-1}$) an increase in orotic aciduria occurred below 7.5 g arginine$\cdot kg^{-1}$ diet. At 250 g $CP \cdot kg^{-1}$ diet, the quantity of arginine necessary to minimize urinary orotic acid was 10 $g \cdot kg^{-1}$ diet, and 0.02 g arginine$\cdot g^{-1}$ of additional crude protein was necessary to prevent increasing orotic acid in urine as crude protein was increased in the diet. (The equation relating grams of arginine per kilogram of diet y to grams of protein per kilogram of diet x with an r^2 of 0.99 was $y = 0.02x + 4.0$). Thus, the MR in a diet that contains 4 kcal $ME \cdot g^{-1}$ at a crude protein concentration of 200 $g \cdot kg^{-1}$ is suggested to be 7.7 $g \cdot kg^{-1}$ diet with an increase of 0.02 g of arginine per gram of crude protein per kilogram of diet above 200 $g \cdot kg^{-1}$ diet. It should be noted that the above regression equation erroneously predicts an arginine requirement of 4 $g \cdot kg^{-1}$ diet when a protein-free diet is fed, indicating that the equation is not linear below the range of protein tested. No hyperammonemia or orotic aciduria has been reported after feeding a protein-free diet to kittens.

Adverse Effects of Excess Consumption

There are no reports of acute toxicity related to large quantities of free arginine in the diet of cats. Taylor (1995) found that when only essential amino acids (methionine was limited to 9 $g \cdot kg^{-1}$ diet) were fed to kittens, arginine at 45 $g \cdot kg^{-1}$ diet (4.7 kcal $ME \cdot g^{-1}$) was associated with a marked increase in blood plasma concentration of arginine to about 1 $mmol \cdot L^{-1}$ (5-10 times normal), and a small decrease in growth rate occurred in the kittens. It thus seems prudent to set the SUL for arginine at 35 $g \cdot kg^{-1}$ diet containing 4.0 kcal $ME \cdot g^{-1}$.

Histidine

Besides its structural role in proteins and glucogenic role, histidine is essential as a precursor of neuroactive and regulatory compounds such as histamine, anserine, and carnosine. Histidine is present at a particularly high concentration in hemoglobin where the imidazole side chain plays a special role in accepting and donating protons during oxygen exchange in the lung and other tissues.

Dog

Signs of Deficiency

Immature beagles fed a histidine-free diet exhibited about the same degree of weight loss and negative nitrogen balance as that found when diets devoid of other essential amino acids were fed (Milner, 1979b). No problems were observed within a week or more in adult dogs given diets devoid of histidine, whereas, after several weeks, weight loss and decreases in plasma histidine, hemoglobin, and albumin and in muscle histidine and carnosine resulted (Cianciaruso et al., 1981). Dogs fed the histidine-free diet tried to avoid eating the diet, became listless, and had reduced activity.

Requirements and Allowances

Growth was markedly depressed when immature beagles were given a diet containing 1.4 g histidine$\cdot kg^{-1}$ diet (Milner, 1979b). Burns and Milner (1982), in a histidine-response experiment, showed a breakpoint for maximal nitrogen retention of weanling beagles (MR) for histidine at 2.1 $g \cdot kg^{-1}$ diet containing about 4.0 kcal $ME \cdot g^{-1}$. These beagles were given a diet of only about 140 g $CP \cdot kg^{-1}$ diet and hemoglobin was not evaluated. Since the crude protein requirement for 6- to 12-week-old puppies is about 180 g $CP \cdot kg^{-1}$ diet, the MR recommended is 3.1 g histidine$\cdot kg^{-1}$ diet (4 kcal $ME \cdot g^{-1}$) for 4- to 14-week-old puppies and 2.0 $g \cdot kg^{-1}$ diet (4 kcal $ME \cdot g^{-1}$) for puppies older than 14 weeks. The quantity of histidine in commercial, dry, expanded diets and various purified diets with which normal, sustained growth has routinely been observed is 4.4 g histidine$\cdot kg^{-1}$ diet containing 4.0 kcal $ME \cdot g^{-1}$.

Adverse Effects of Excess Consumption

No reports could be found on acute or chronic toxicity related to feeding large quantities of free histidine to dogs.

Cats

Signs of Deficiency

Diets devoid of histidine resulted in body weight loss in kittens of about 5 $g \cdot d^{-1}$, which is less than occurs when any

other essential amino acid is omitted from the diets (Rogers and Morris, 1979). This response is similar to that noted in other species, including humans, where it was assumed for many years that histidine was dispensable because, in short-term experiments, the subjects maintained nitrogen balance in the absence of dietary histidine. Further work has shown that in virtually all species, histidine is an essential amino acid, but histidine available from the turnover of hemoglobin provides sufficient quantities to prevent negative nitrogen balance in the short term while the animal has a gradual decrease in hemoglobin. Thus, the maintenance of hemoglobin concentration is an important variable to use in determining the histidine requirement. A marginal deficiency of histidine, even when an adequate quantity is provided for maximal weight gain, has been shown to cause cataracts (Quam et al., 1987), thus providing another important variable for use in determining the MR of histidine.

Requirements and Allowances

Anderson et al. (1980b) showed that 3 g histidine·kg^{-1} diet was sufficient for maximal weight gain of young kittens. Further work by Quam et al. (1987) showed that both maximal weight gain and nitrogen retention occurred at 2 g·kg^{-1} diet (4.7 kcal ME·g^{-1} diet), but maximal blood hemoglobin concentration was not reached until the diet contained 3 g histidine·kg^{-1} diet. Further, they showed that cataracts occurred when kittens were fed a diet containing only 2 g of histidine per gram of diet for 4-5 months, confirming the MR for histidine for the growing kitten to be 2.6 g·kg^{-1} diet containing 4 kcal ME·g^{-1}. The concentration of histidine found in commercial, dry, expanded diets and various purified diets with which normal, sustained growth has routinely been observed is 4.7 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Adverse Effects of Excess Consumption

No dose-response studies could be found of acute or chronic toxicity related to feeding large quantities of free histidine to cats. Taylor et al. (1998) found that when only essential amino acids were included in the diet (methionine and arginine were limited to 9 and 22.5 g·kg^{-1} diet, respectively) (4.5 kcal ME·g^{-1} diet), 24.4 g histidine·kg^{-1} diet did not cause any observable clinical signs. Thus, the SUL is > 22 g histidine·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Isoleucine

Isoleucine is both ketogenic and glucogenic. Its only known essential function is as a constituent of proteins.

Dogs

Signs of Deficiency

Immature beagles fed an isoleucine-free diet exhibit a marked depression in food intake, a body weight loss of 32 g·d^{-1} and negative nitrogen balance (Milner, 1979b). No other specific clinical signs were reported at the end of the 14-day experiment.

Requirements and Allowances

Growth was depressed about 30 percent when the concentration of isoleucine in the diet of immature beagles was decreased from 8.2 to 4.1 g·kg^{-1} (Milner, 1979b). Burns et al. (1984), in an isoleucine-response experiment, showed a breakpoint (MR) for maximal nitrogen retention of weanling beagles 12 weeks of age at 4.0 g isoleucine·kg^{-1} diet containing about 4.0 kcal ME·g^{-1}. Since these beagles were fed only about 140 g of crude protein per kilogram of diet and the requirement for 6- to 12-week-old puppies is about 180 g crude protein, 4.0 g isoleucine·kg^{-1} diet is taken as the MR for 14-week-old puppies and 5.2 g·kg^{-1} diet containing 4 kcal ME·g^{-1} for 4- to 14-week-old puppies. The concentration of isoleucine in commercial, dry, expanded diets and various purified diets with which normal, sustained growth has routinely been observed is 5.0 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Adverse Effects of Excess Consumption

No reports could be found on acute or chronic toxicity related to feeding large quantities of free isoleucine to dogs; so no SUL can be established.

Cats

Signs of Deficiency

Removal of isoleucine from the diet of kittens results in a weight loss of about 7-10 g·d^{-1} (Rogers and Morris, 1979; Anderson et al., 1980c). When kittens were fed subadequate isoleucine at 2.2 g·kg^{-1} diet (about 4.7 kcal ME·g^{-1} diet, Hargrove et al., 1984), growth was suboptimal, and, after a few days they developed porphyrin-type crusty material around the eyes, nose, and mouth, a rough hair coat with desquamation of the outer layer of the epidermis on the pads of the paws with cracking and occasional lesions, lethargy, slow righting reflex, and incoordination. All clinical signs were corrected after adequate isoleucine supplementation. Staphylococcal species were cultured from the conjunctiva of the deficient kittens but disappeared without antibiotic treatment upon supplementation with sufficient isoleucine; thus, the kittens appeared to have impaired resistance to common dermal bacteria. Similar mild clinical signs were

observed in kittens fed 3.8 g isoleucine·kg^{-1} diet (4.7 kcal ME·g^{-1} DM) after several weeks.

Requirements and Allowances

Anderson et al. (1980c), using maximal kitten weight gains of 10-12 g·d^{-1}, reported that 3 g isoleucine·kg^{-1} diet (about 4.7 kcal ME·g^{-1}) was sufficient for maximal growth of young kittens. Further work by Hargrove et al. (1984) showed that both maximal weight gains (about 35 g·d^{-1}) and nitrogen retention occurred at about 5 g·kg^{-1} diet (4.7 kcal ME·g^{-1} diet). Thus, at 4 kcal ME·g^{-1} the MR is 4.3 g isoleucine·kg^{-1} diet. The concentration in commercial, dry, expanded diets and various purified diets with which normal, sustained growth has routinely been observed, is 7.7 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Adverse Effects of Excess Consumption

There are no reports of acute or chronic toxicity related to large quantities of free isoleucine in the diet of cats. Hargrove et al. (1988) fed 100 g isoleucine·kg^{-1} diet containing about 180 g crude protein and 240 g fat per kilogram without any observable decrease in weight gain or other adverse clinical signs. Thus, the SUL for isoleucine is >87 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Leucine

Leucine is a strongly ketogenic, branched-chain amino acid, since upon oxidation the carbon forms a ketone body and an acetyl coenzyme A (CoA) molecule. The only known structural role of leucine is as a constituent of proteins. Leucine has a role in regulating the catabolism of all branched-chain amino acids via inhibition of branched-chain δ-ketoacid dehydrogenase (BCKAD) kinase by its δ-ketoacid, δ-ketoisocaproic acid (Harris et al., 2001). This kinase phosphorylates BCKAD to decrease its activity. Since the branched-chain transaminase is present in excess relative to BCKAD, excess leucine results in activation of BCKAD, which, in turn, causes an increase in the catabolism of all branched-chain amino acids. The branched-chain transaminase is present in most tissues except liver, it is not rate limiting, and the reaction is readily reversible. Leucine has been reported to enhance protein synthesis directly and indirectly by increasing plasma insulin (Balage et al., 2001; Anthony et al., 2002) and suppressing protein degradation (Nagasawa et al., 2002) in skeletal muscle. Thus, leucine has a marked anabolic effect following absorption. This regulatory role may have evolved since leucine is never limiting in natural foods for animals and neither isoleucine nor valine is known to be limiting. Thus, when protein is ingested, leucine increases protein synthesis and decreases protein degradation, both of which increase the efficiency of utilization of all the essential amino acids including leucine for maintenance, growth, or reproduction. Since leucine controls it own degradation and that of isoleucine and valine, this prevents potential toxicity from branched-chain amino acids at even high dietary concentrations.

Dogs

Signs of Deficiency

Immature beagles fed a leucine-free diet exhibit a marked depression in food intake, weight loss (about 34 g·d^{-1}), and negative nitrogen balance (Milner, 1979a). No specific clinical signs were reported at the end of the 14-day experiment.

Requirements and Allowances

Growth was depressed about 10 percent when leucine was decreased from 11 to 5.5 g·kg^{-1} diet fed to immature beagles (Milner, 1979a). Burns et al. (1984), in a dose-response experiment, showed a breakpoint at 6.0 g leucine·kg^{-1} diet (4.0 kcal ME·g^{-1}) for maximal nitrogen retention of weanling beagles at 11 weeks of age. Although not significantly different, weight gain was greatest at 12 g leucine·kg^{-1} diet, and the greatest nitrogen retention occurred at 10 g leucine·kg^{-1} diet. Delaney et al. (2001), using 8-week-old beagle puppies, studied the interaction between graded levels of leucine and dietary crude protein. They found that, although 140 g of crude protein per kilogram of diet did not support maximal weight gain, the leucine requirement was the same (11 g·kg^{-1} diet containing 4.3 kcal ME·g^{-1}) for 8- to 14-week-old beagles fed 140 g and those fed 280 g of crude protein per kilogram of diet. However, for beagles >14 weeks of age, the breakpoint for both protein groups was 7 g leucine·kg^{-1} diet. From these results, the MR for 4- to 14-week-old puppies is 10.3 g·kg^{-1} and for puppies >14 weeks is 6.5 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1} diet. The quantity in commercial, dry, expanded diets and various purified diets with which normal, sustained growth has routinely been observed is 20 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Adverse Effects of Excess Consumption

No reports could be found on acute or chronic toxicity related to feeding large quantities of free leucine to dogs fed complete, balanced diets, so no SUL can be established. There is a report that the addition of 12 g leucine·kg^{-1} diet containing 180 casein·kg^{-1} and no added niacin induced black tongue in dogs (Belavady et al., 1967), but this could not be replicated (Manson and Carpenter, 1978).

Cats

Signs of Deficiency

Removal of leucine from the diet of kittens resulted in a weight loss of about 7 g·d^{-1} (Rogers and Morris, 1979), but

no other clinical signs were noted during the short (10-day) experiment.

Requirements and Allowances

Anderson et al. (1980c), using maximal weight gains of 10-15 $g \cdot d^{-1}$, reported that weight gains of young kittens plateaued at 12 g leucine·kg^{-1} diet (about 4.7 kcal ME·g^{-1}). Work by Hargrove et al. (1984) showed that weight gains of about 32 $g \cdot d^{-1}$ occurred at about 9 g leucine·kg^{-1} diet, whereas maximal nitrogen retention occurred at about 12 g leucine·kg^{-1} diet or higher (4.7 kcal ME·g^{-1} diet). Thus, at 4 kcal ME·g^{-1} the MR of kittens for leucine is 10.2 g·kg^{-1} diet. The concentration in commercial, dry, expanded diets and various purified diets with which normal, sustained growth has routinely been observed is 18 g leucine·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Adverse Effects of Excess Consumption

No reports could be found relating clinical signs of acute or chronic toxicity to feeding large quantities of free leucine to cats. Hargrove et al. (1988) fed 100 g leucine·kg^{-1} diet containing about 180 g crude protein and 240 g fat per kilogram without any observable decrease in weight gain or other adverse clinical signs; in fact, weight gain was increased. Thus, the SUL for leucine is >87 g·kg^{-1} diet (4.0 kcal ME·g^{-1}). If isoleucine and valine were limiting (80 percent of the requirement), there was a transitory decrease in weight gain when 100 leucine·kg^{-1} diet was added, indicating only a weak leucine-isoleucine and valine antagonism in kittens. Kittens under similar conditions (i.e., isoleucine and valine limiting), when offered a choice, chose a high-leucine diet (Hargrove et al., 1994). Thus, high dietary leucine, even eight to nine times above the requirement, seems to be a positive influence on food intake of kittens fed a low-protein diet.

Lysine

Lysine is weakly ketogenic; it is a constituent of proteins, acts as a precursor of other constituents such as hydroxylysine, and is important for cross-linkages that occur in collagen. Lysine, because of its ε-amino group, is important for the secondary structure of proteins as it is normally charged, and it can also be methylated or acetylated. Lysine is deaminated by intestinal bacteria to produce the foul-smelling amine cadaverine. Lysine, post-translationally, is methylated to trimethyllysine, which after proteolysis is the precursor of carnitine. Since lysine concentration is low in cereals and it readily forms Maillard reaction products with glucose and heat, it is often the limiting amino acid when low-protein, cereal-based diets are fed. The free L-form is relatively cheap and has been available for decades for supplementing feeds.

Dogs

Signs of Deficiency

Immature beagles fed a lysine-free diet exhibited a marked depression in food intake and lost about 29 g BW per day, about the same degree of weight loss and negative nitrogen balance found when diets devoid of other essential amino acids were fed (Milner, 1979a). No specific clinical signs were reported at the end of the 14-day experiment.

Requirements and Allowances

Milner (1981) reported that beagles (less than 14 weeks old) given a diet containing 140 g of amino acids per kilogram of diet achieved maximal weight gain and nitrogen retention at a dietary lysine concentration of 5.8 g·kg^{-1} for females and 6.9 g·kg^{-1} for males. When the diet contained 280 g of amino acids per kilogram, nitrogen retention increased up to 5.8 g lysine·kg^{-1} diet, but higher levels of lysine were not used. Using diets based on free amino acids and intact protein supplemented with lysine, respectively, Hirakawa and Baker (1986) reported the lysine requirements for weanling pointer puppies to be 7 g lysine·kg^{-1} diet using the amino acid diet and 8 g lysine·kg^{-1} diet using intact protein (diets containing about 3.9 kcal ME·g^{-1} diet). These results, indicating a higher requirement for the intact protein diet, are consistent with a bioavailability of about 85 percent for lysine from protein concentrates for dogs (Murray et al., 1997). From these results the MR for lysine for growth of 4- to 14-week-old puppies is 7 g·kg^{-1} and for >14-week-old puppies 5.6 g·kg^{-1} diet containing 4.0 kcal ME·kg^{-1} diet. The concentration in commercial, dry, expanded diets and various purified diets with which normal, sustained growth has routinely been observed is 9.0 g lysine·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Adverse Effects of Excess Consumption

A lysine-arginine antagonism was reported by Czarnecki et al. (1985) in growing English pointer puppies. They found that, although 10 or 20 g of extra free lysine per kilogram of diet had no effect, 40 g excess lysine in the diet caused a growth depression and classical clinical signs of arginine deficiency (emesis, increased plasma ammonia, and orotic aciduria) when the diet contained 4 g arginine·kg^{-1}. An additional 4 g arginine prevented the clinical signs and improved weight gain but did not appear to fully restore it. The excess lysine caused a generalized amino aciduria. Only about 4 percent of the ingested arginine was excreted, and the excess lysine caused no increase in liver arginase as occurs in birds (Nesheim, 1968); therefore, the mechanism of antagonism in dogs remains unclear. The SUL for lysine is >20 and <40 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Cats

Signs of Deficiency

Removal of lysine from the diet of kittens resulted in a weight loss of about 11 $g \cdot d^{-1}$ (Rogers and Morris, 1979), but no other clinical signs were noted during the short 10-day experiment. Although graying of feathers in birds (Vohra and Kratzer, 1957) and hair in rats (Vohra and Kratzer, 1956) has been known for many years to occur as a result of lysine deficiency, this has not been reported in cats, perhaps because it is unusual for lysine to be limiting in cat foods and no long-term experiments on lysine deficiency in cats have been reported.

Requirements and Allowances

Jansen et al. (1975) demonstrated that the rate of body weight gain of cats given a diet based on wheat gluten was increased by a lysine supplement. Anderson et al. (1979a), using maximal weight gain as the determining variable, reported that 8 g lysine·kg^{-1} diet (about 4.7 kcal ME·g^{-1}) supported maximal weight gain of young kittens. Further work by Morris et al. (2004) showed that both weight gain and nitrogen retention were maximized at 8 g lysine·kg^{-1} diet (4.7 kcal ME·g^{-1} diet). Thus, at 4 kcal ME·g^{-1}, the MR for lysine is set at 6.8 $g \cdot kg^{-1}$ diet. The concentration of lysine in commercial, dry, expanded diets and various purified diets with which normal, sustained growth has routinely been observed is 12 $g \cdot kg^{-1}$ diet containing 4.0 kcal ME·g^{-1}.

Adverse Effects of Excess Consumption

No reports were found of clinical signs of acute or chronic toxicity related to large quantities of free lysine in the diet of cats. Taylor et al. (1998) gave a diet containing 65 g lysine·kg^{-1} (4.5 kcal ME·g^{-1}) to kittens (i.e., about eight times the requirement), without any observable adverse clinical signs. The SUL for lysine is > 58 $g \cdot kg^{-1}$ diet (4.0 kcal ME·g^{-1}).

Methionine and Cyst(e)ine

Methionine is generally the most limiting amino acid in a diet formulated using natural ingredients for cats and is often first or second limiting for dogs. Since methionine is a *methyl group* donor, a part of the coenzyme (*S*-adenosylmethionine) for methyl group transfer, and an amino acid present in proteins, a deficiency of methionine results in a multitude of metabolic aberrations. These include interference with cell replication (defect in methylating RNA and/or DNA) and phospholipid synthesis (causing fatty liver). During catabolism, the carbon skeleton of methionine is glucogenic. Cysteine is an important component of proteins for their secondary structure and a major constituent of hair and glutathione. Since methionine serves as a precursor to cysteine, cysteine is a dispensable amino acid. Because cysteine is made only from methionine and can provide about one-half of the total need for sulfur amino acids, cysteine and methionine must both be considered when establishing the total sulfur amino acid requirement. Therefore, the requirements are presented as the MR of methionine when there is excess cysteine in the diet, and the total sulfur amino acid requirement, which can be met with only methionine, but commonly involves a combination of methionine and cysteine. Cysteine cannot be converted to methionine; so the MR of methionine must be met with methionine. Since methionine is often limiting in animal diets, DL-methionine, which is commercially available and relatively cheap compared to the same amount of methionine supplied by protein, is often added to dog and cat diets. Therefore, the efficiency of utilization of DL-methionine in replacing L-methionine is given for both dogs and cats.

Over a period of two decades (Stekol, 1935; Miller, 1944; Allison, 1947, 1956), it was shown in both growing and adult dogs that methionine (either the L- or the DL-form) had a unique effect in reducing nitrogen loss and maintaining serum albumin when dogs were fed a low-protein or a protein-free diet. Although this phenomenon does not appear to have been studied recently, it could be the result of methionyl-tRNA being used as the initiator codon for protein synthesis and adequate methionine may be particularly important in the liver for this purpose.

Cysteine is an important precursor for the synthesis of glutathione and felinine. Glutathione is an antioxidant that has been studied extensively (Flohe, 1988). Felinine, a branched-chain, sulfur-containing α-amino acid (2-amino-7-hydroxy-5,5-dimethyl-4-thiaheptanoic acid) commonly found in the urine of selected members of the felids, including domestic cats, has not been studied extensively. Felinine was first isolated by Westall (1953) who suggested its structure, which was verified by Trippett (1957). The biological function of felinine has not been fully established. Although it has been suggested that felinine is involved in lipid metabolism (Shapiro, 1962; Roberts, 1963), the most widely accepted possible role for felinine, or its odiferous breakdown product in urine, is as a pheromone, which is of importance in territorial marking (Hendriks, 1995a). Roberts (1963) reported that kittens, before sexual maturity (<8 months old), did not excrete any felinine and that adult males excreted more than did adult females who increased their urinary output when given testosterone. They also showed, however, that giving estrogen to adult neutered male cats had no effect on urinary felinine excretion. Hendriks et al. (1995b) reported that adult intact male cats excreted 95 mg felinine per day (29 $mg \cdot d^{-1}$ for neutered males), whereas adult intact females excrete only 19 $mg \cdot d^{-1}$ (13 $mg \cdot d^{-1}$ for neutered females). Recent evidence (Hendriks et al., 2001; Rutherfurd et al., 2002) indicates that felinine is synthesized in the liver from cysteine and an intermediate in the pathway of cholesterol biosynthesis, is conjugated to γ-glutamylfelinylglycine, and is then trans-

ported to the kidney where hydrolysis occurs to produce free felinine for urinary excretion. The quantity of sulfur containing amino acids in the diet needed for synthesis of the normal quantity of felinine excreted by adult male cats would be about 60 mg·d^{-1} or about 20-25 percent of the MR for maintenance or 5-10 percent of the lower end of normal sulfur amino acid intake.

Dogs

Signs of Deficiency

The removal of methionine from a diet containing 3.5 g·kg^{-1} of cystine for puppies (Milner, 1979b) or adult dogs (Rose and Rice, 1939) resulted in an immediate decrease in food intake and severe weight loss. The puppies exhibited dermatitis, but no other gross lesions were reported. Hirakawa and Baker (1985), using amino acid diets and intact protein, reported that excess dietary cystine together with a methionine deficiency resulted in severe weight loss of puppies, swelling and reddening of the skin, and with time, increased severity of dermatosis on the front foot pads. These lesions became necrotic and hyperkeratotic with ulceration of the epithelium. When methionine was increased in the diet, the lesions rapidly disappeared. These clinical signs were similar to those reported for kittens (Strieker, 1991). When dogs were given high-carbohydrate, high-cholesterol diets that contain protein near their requirement but are borderline in methionine and deficient in taurine, they consistently develop pigment gallstones not corrected with taurine but corrected with methionine supplementation (Dawes et al., 1989; Christian and Rege, 1996). The mechanism is not understood.

Requirements and Allowances

Milner (1979b) obtained maximal weight gains with immature (1.5-2.2 kg) beagles given an amino acid diet containing about 140 g of crude protein per kilogram of diet with 2.1 g methionine·kg^{-1} and 3.5 g cystine·kg^{-1} (4 kcal ME·g^{-1}). In a methionine-response experiment, the same group (Burns and Milner, 1981), using immature (2.8-4.4 kg) beagles and an energy content of diets at 4.3 kcal ME·g^{-1}, concluded that the requirements for total sulfur amino acids and methionine were 3.9 and 2.0 g·kg^{-1} diet, respectively. Blaza et al. (1982), using Labradors and beagles with isolated soybean protein-based diets with a crude protein and energy contents of about 200 g·kg^{-1} and 4.7 kcal ME·g^{-1} diet, respectively, concluded that the requirement for total sulfur amino acids was 6.3 g·kg^{-1} diet. These researchers found that 2 weeks was not sufficient to allow the animals to come to a steady weight gain. Hirakawa and Baker (1985), using English pointer puppies and amino acid diets containing about 140 CP·kg^{-1} diet and 4.0 kcal ME·g^{-1}, concluded that the requirements for total sulfur amino acids and methionine were 4.5 and 2.3 g·kg^{-1} diet, respectively. When the longer-term experiments are considered, along with the MR for crude protein of 180 g·kg^{-1} diet, the MRs for total sulfur amino acids and methionine are 5.6 and 2.8 g·kg^{-1}, respectively, of diets containing 4.0 kcal ME·g^{-1}, for 4- to 14-week-old puppies and 4.2 and 2.1 g·kg^{-1} diet for puppies over 14 weeks old. The concentrations of total sulfur amino acids and methionine in commercial, dry, expanded diets and various purified diets that sustain normal growth are 6.2 and 3.2 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}, respectively.

Adverse Effects of Excess Consumption

Oral administration of about 1 g methionine·kg^{-1} BW every 4 hours for 24 hours caused no acute clinical signs in normal dogs but caused severe clinical signs similar to hepatic coma in dogs with portacaval shunts (Merino et al., 1975). The clinical signs appeared to be caused by the post-transamination metabolites methanethiol and dimethyl disulfide, and not by metabolites produced in the normal (transulfurylation) pathway of methionine catabolism. Biourge et al. (2002) reported methionine toxicosis in six hunting dogs fed a single meal of about 300 g of a normal diet containing 47 g DL-methionine·kg^{-1}, apparently the result of a formulation error. Within 3-4 hours, the dogs were ataxic, became disorientated and hyperactive, and developed lethargy, tremors, vomiting of undigested food, and ptyalism. The youngest dog, 6 months old, was very depressed, was unable to stand, and had episodes of seizures. Merino et al. (1975) did not stipulate whether they used L- or DL-methionine. If they used L-methionine, D-methionine would appear to be considerably more toxic than the L-form, presumably because all of the D-form goes through the δ-ketoacid, which would increase acutely the quantity of methanethiol and dimethyl disulfide. Since there are no reports of dose-response curves with L-methionine added to dog diets, it is not possible to determine the SUL for L-methionine; however, it would appear that the SUL for DL-methionine is well below 47 g·kg^{-1} diet containing 4 kcal ME·g^{-1}.

Cats

Signs of Deficiency

Removal of methionine from the diet of kittens and adult cats resulted in body weight loss (Teeter et al., 1978a). Rogers and Morris (1979) reported that among the essential amino acid deficiencies, the greatest weight loss in kittens (except for arginine deficiency) occurred with a methionine-devoid diet (19.5 g·d^{-1}). Clinical signs of severe chronic methionine deficiency included lethargy and abnormal secretions from the eyes that occlude the eyelids. Further work by Strieker (1991) showed that cystine supplementation of a methionine-deficient diet (1.6 g methionine·kg^{-1} diet) resulted in severe perioral and footpad lesions of young kit-

tens. These clinical signs were similar to that of prolonged protein deficiency, indicating that methionine is most likely the first limiting amino acid when there is a deficiency of crude protein in cats.

Requirements and Allowances

Ritter and Owens (1974), using a casein-gelatin based diet, suggested a methionine requirement for growing kittens of 9 g·kg^{-1} diet. Teeter et al. (1978b), using amino acid-based diets, showed that 4.5 g methionine·kg^{-1} diet (4.7 kcal ME·g^{-1}) was sufficient for maximal weight gain when 6 g cystine·kg^{-1} diet was present. When methionine was present in the diet at 4.5 g·kg^{-1}, 4.5 g cystine·kg^{-1} diet was sufficient to support maximal growth. Schaeffer et al. (1982a), using amino acid diets devoid of cystine, concluded that 7.5 g methionine·kg^{-1} diet (4.7 kcal ME·g^{-1}) was sufficient for maximal weight gain and nitrogen retention. Smalley et al. (1983), using both weight gain and nitrogen retention but with 6 g cystine·kg^{-1} diet, found maximal nitrogen retention with 3.9 g methionine·kg^{-1} diet (4.7 kcal ME·g^{-1}). From methionine-response curves for weight gain and nitrogen retention, Strieker (1991) determined the methionine requirement of kittens given amino acids diets containing cystine and four different levels of crude protein. The requirement was 4.5 g methionine·kg^{-1} diet (4.7 kcal ME·g^{-1}) with dietary crude protein concentrations up to 300 g·kg^{-1} diet. The requirement appeared to decrease to 3.5 g·kg^{-1} diet when the diet contained 500 g crude protein per kilogram. From these results, the MR for methionine was estimated to be 3.5 g·kg^{-1} and the total sulfur amino acid MR to be 7.0 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

The D-isomer of methionine is well utilized (Teeter et al., 1978a) by growing kittens, and dose-response studies with both the L- and the D-forms (Smalley et al., 1993) indicated that utilization of the D-form was about 80-90 percent that of the L-form, using nitrogen retention as the variable. The concentrations of methionine and total sulfur amino acids in commercial, dry, expanded diets and various purified diets with which normal, sustained growth has routinely been observed are 5.0 and 9.0 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}, respectively. All of these sulfur amino acid requirements have been determined with ample choline in the diet, and it has been shown that choline deficiency causes fatty liver with fat infiltration primarily in the periportal spaces, not around the centrolobular vein as occurs in several other species (Da Silva et al., 1959). Choline spares some methionine in the cat (Anderson et al., 1979c; Schaeffer et al., 1982b).

Adverse Effects of Excess Consumption

Cats given 1.0 g DL-methionine·kg BW^{-1}·d^{-1} develop severe hemolytic anemia and a marked increase in methemoglobin concentration with Heinz body formation by 6 days (Maede et al., 1987). Cats given 0.5 g·kg BW^{-1}·d^{-1} (DL-methionine) for 52 days had moderate Heinz body anemia with methemoglobinemia by day 17, but later recovered from the anemia, indicating some adaptation to the excess methionine. In vitro incubation of erythrocytes with methionine at 10 mmol·L^{-1} did not produce methemoglobin or Heinz bodies, whereas incubation with the abnormal methionine metabolite 3-methyl thiopropionate caused some increase in both. Fau et al. (1987b) fed growing kittens a purified diet containing 180 g casein·kg^{-1} diet (containing about 5 g methionine·kg^{-1}) and an additional 20, 30, or 40 g L-methionine·kg^{-1} and found that all three concentrations of methionine caused a decrease in food intake and weight gain. Kittens given the 30 g methionine·kg^{-1} diet did not readily adapt and showed no weight gain, whereas those given the 40 g methionine·kg^{-1} diet continuously lost weight for 6 weeks. Fau et al. (1987a) measured the enzymes involved in methionine catabolism and found that in cats these enzymes were not up-regulated to the same degree by excess dietary methionine as in rats. Schaeffer et al. (1982a), in a methionine-response experiment to determine the requirement, found only a slight decrease (not significantly different) in nitrogen retention at 15 g methionine·kg^{-1} diet containing 4.7 kcal ME·g^{-1}. The concentration of methionine in plasma of kittens given the 15-g methionine·kg^{-1} diet was about 10 times normal, at about 540 nmol·mL^{-1}. Taylor et al. (1996) found a decreased weight gain and elevated concentration of plasma methionine at 648 nmol·mL^{-1} in kittens given a diet containing 18 g methionine·kg^{-1}. The SUL for the growing kitten is 13 g L-methionine·kg^{-1} diet containing 4.0 kcal ME·g^{-1}. This concentration is about the available methionine content of an all-meat diet containing 300-350 g fat·kg^{-1} diet (dry matter), and it would be predicted that peptide-bound methionine in protein would be less toxic than that provided in the free form. Thus, it is unlikely that cats eating natural prey would exceed the SUL for methionine.

Phenylalanine and Tyrosine

Catabolism of phenylalanine for energy through tyrosine produces intermediates that are both glucogenic and ketogenic. Although tyrosine is a dispensable amino acid, it is made in animals only from phenylalanine, and tyrosine spares about one-half of the phenylalanine needed by all species examined including dogs and cats. Thus, it is appropriate to consider the amount of phenylalanine required as the sum of phenylalanine plus tyrosine, provided the level of tyrosine in the diet is not higher than that of phenylalanine. Phenylalanine and tyrosine have not been shown to be the most limiting amino acids for growth or nitrogen balance in diets sufficient in protein or in commercial diets formulated using natural ingredients for dogs and cats. However, Morris and coworkers (Yu et al., 2001; Anderson et al., 2002) in cats and Biourge and Sergheraert (2002) in dogs have re-

cently shown that at least twice as much phenylalanine (or phenylalanine plus tyrosine) is required for maximal black hair color (adequate eumelanin in hair to produce the black color) as for growth. Other metabolic needs for phenylalanine and tyrosine, besides the amount needed for protein synthesis, include the synthesis of key metabolites such as thyroid hormones and catecholamines.

Dogs

Signs of Deficiency

Immature beagles fed a phenylalanine-free diet containing 3.5 g tyrosine·kg^{-1} exhibited a marked depression in food intake and lost about 19 g BW·d^{-1}, which is somewhat less than that found when other essential amino acid-devoid diets were fed (Milner, 1979a). No specific clinical signs were reported at the end of the 14-day experiment. Biourge and Sergheraert (2002) have reported a reddish-brown hair coat in black dogs fed commercial, dry, expanded diets that contained less than twice as much phenylalanine plus tyrosine as that required for maximal weight gain.

Requirements and Allowances

Growth was depressed about 10 percent when immature beagles were given a diet containing 3.5 g tyrosine·kg^{-1} and phenylalanine was decreased from 11.6 to 5.8 g·kg^{-1} diet (Milner, 1979a). Milner et al. (1984), in two separate phenylalanine-response experiments, showed breakpoints for maximal nitrogen retention by weanling beagles at 10 weeks of age (MR) for phenylalanine in the absence of tyrosine at 8.0 g·kg^{-1} and between 8 and 10 g·kg^{-1} diet (4.0 kcal ME·g^{-1}). Since these beagles were fed only about 140 g CP·kg^{-1} diet and the crude protein requirement for 6- to 12-week-old puppies is about 180 g, 8.0 g·kg^{-1} diet is taken as the MR for 14-week-old puppies and 10.4 g phenylalanine plus tyrosine per kilogram of diet is taken as the MR for 4- to 14-week-old puppies ingesting diets containing 4.0 kcal ME·g^{-1} diet. Milner et al. (1984) further showed that when the sum of phenylalanine plus tyrosine is suboptimal (6 g·kg^{-1} diet), the lowest ratio of phenylalanine to tyrosine resulting in maximal weight gain and nitrogen retention for that concentration of total phenylalanine and tyrosine was 2:1. However, since maximal growth or nitrogen retention was not achieved, this ratio is open to question as the minimal ratio. Results from puppies fed purified diets containing various levels of phenylalanine plus tyrosine to prevent the reddish brown hair in black dogs have not been reported. The concentrations of phenylalanine and phenylalanine plus tyrosine in commercial, dry, expanded diets and various purified diets with which normal, sustained growth has routinely been observed are, respectively, 8.3 and 12.3 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}. These experiments with dogs have not been evaluated for the completeness of eumelanin formation in dogs to prevent a reddish-brown color in black hair.

Adverse Effects of Excess Consumption

No reports could be found on acute or chronic toxicity related to feeding large quantities of free phenylalanine or tyrosine to dogs fed complete, balanced diets, so no SUL can be established.

Cats

Signs of Deficiency

For kittens, removal of phenylalanine from a diet containing 10 g tyrosine·kg^{-1} resulted in a weight loss of about 10 g·d^{-1}, whereas if tyrosine was left out of a diet containing 7.5 g phenylalanine·kg^{-1}, normal weight gain occurred (Rogers and Morris, 1979). No other clinical signs were reported during these short (7-14 days) experiments. In experiments lasting 3-4 months, Yu et al. (2001) observed that the black hair coat of kittens turned reddish-brown when the sum of phenylalanine and tyrosine was suboptimal. In further work in which kittens were fed 10 g phenylalanine·kg^{-1} diet and only 2 g tyrosine·kg^{-1} diet for more than 6 months (Anderson, 2002), the cats showed clinical signs of neurological dysfunction involving an abnormal, uncoordinated gait with the tail bending forward over the back. The cats were also hyperactive, hypersalivated, and emitted frequent vocalizations. Histologically, the nerves showed marked Wallerian degeneration of axons with secondary myelin collapse. More of either phenylalanine or tyrosine prevented or corrected these clinical abnormalities.

Requirements and Allowances

Anderson et al. (1980b), in a series of growth experiments in kittens using various dietary concentrations of phenylalanine and tyrosine, reported that maximal weight gains (16-18 g·d^{-1}) occurred in growing kittens given 10 g phenylalanine plus tyrosine·kg^{-1} and that tyrosine provided half of the total requirement (4.7 kcal ME·g^{-1}). Williams et al. (1987), found maximal weight gains of 25 g·d^{-1} and, on this basis plus nitrogen retention data from kittens, reported the requirement for phenylalanine alone in the diet to be 7.5 g·kg^{-1}, whereas with 10 g tyrosine·kg^{-1} in the diet the phenylalanine requirement was 3.5 g·kg^{-1}. Recently, Anderson et al. (2002) found that the quantity of phenylalanine plus tyrosine necessary to maximize black hair color was 18 g·kg^{-1} diet, but eumelanin in black hair appeared to increase even beyond this dietary concentration. From these results, the MR necessary to sustain both fully black hair coat and maximal nitrogen retention is 15.3 g phenylalanine plus tyrosine per kilogram of a diet containing 4.0 kcal ME·g^{-1} with the MR for phenylalanine (with 14 g tyrosine·kg^{-1} diet)

as 4.0 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}. The concentrations of phenylalanine plus tyrosine and of phenylalanine, respectively, in commercial, dry, expanded diets and various purified diets that sustain maximal weight gain are 15.8 and 10.3 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Adverse Effects of Excess Consumption

No reports could be found on clinical signs of acute or chronic toxicity related to feeding large quantities of free phenylalanine to cats. Taylor et al. (1998) fed kittens 33 g phenylalanine·kg^{-1} and 37 g tyrosine·kg^{-1} in a diet containing about 4.5 kcal ME·kg^{-1} diet (i.e., about four times the requirement to prevent black hair from turning reddish-brown) without any observable adverse clinical signs. Herwill (1994) fed increasing tyrosine concentrations up to 80 g·kg^{-1} diet (4.7 kcal ME·g^{-1}) for 82 days without any observable clinical signs except a nonsignificant decrease in food intake. Thus, the SUL for phenylalanine is >29 and the SUL for tyrosine is 68 g·kg^{-1} diet (4.0 kcal ME·g^{-1}).

Threonine

Threonine, a glucogenic amino acid, is not known to have any unique precursor functions except possibly in the formation of glycine via threonine aldolase in some species. The hydroxyl group on the side chain of threonine often serves as the site of phosphorylation-dephosphorylation reactions that control the activities of various proteins and enzymes. Since threonine cannot be reversibly transaminated, the L-form is required "intact" and no other organic form is known that can be substituted in the diet for L-threonine. Hammer et al. (1996b) examined the various metabolic pathways of threonine catabolism in cats and concluded that threonine aldolase is not active in cats and that threonine is catabolized about equally by threonine 3-dehydrogenase and threonine dehydratase. Increasing dietary protein concentration from 200 to 500 g·kg^{-1} diet increased threonine 3-dehydrogenase about 70 percent and threonine dehydratase one- to fourfold.

Dogs

Signs of Deficiency

Immature beagles fed a threonine-free diet exhibited a marked depression in food intake and lost about 29 g BW·d^{-1}, which is similar to that found when other essential amino acid-devoid diets were fed (Milner, 1979a,b). No specific clinical signs were reported at the end of the 14-day experiment.

Requirements and Allowances

Weight gain of immature beagles was depressed about 50 percent when threonine was decreased from 8.2 to 4.1 g·kg^{-1} in their diet (Milner, 1979b). Burns and Milner (1982), in a threonine-response experiment, showed a breakpoint for maximal nitrogen retention of weanling beagles at 15 weeks of age (MR) for threonine at 5.0 g·kg^{-1} diet containing about 4.0 kcal ME·g^{-1}. Since these beagles were fed only about 140 g of crude protein per kilogram of diet and the crude protein requirement for 6- to 12-week-old puppies is about 180, the 5.0 g·kg^{-1} diet is taken as the MR for 14-week-old puppies and 6.5 g·kg^{-1} diet is taken as the MR for 4- to 14-week-old puppies ingesting diets containing 4.0 kcal ME·g diet. The concentration of threonine in commercial, dry, expanded diets and various purified diets with which normal, sustained growth has routinely been observed is 8.5 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Adverse Effects of Excess Consumption

No reports could be found of acute or chronic toxicity in dogs related to large quantities of free threonine in complete, balanced diets, so no SUL can be established.

Cats

Signs of Deficiency

Removal of threonine from the diet of kittens resulted in a depression in food intake and a body weight loss of about 15 g·d^{-1} (Rogers and Morris, 1979). Titchenal et al. (1980) fed kittens suboptimal concentrations of threonine (4 or 5 g·kg^{-1} diet) and found as early as the fifth day that kittens developed slight tremors in the limbs, jerky head and leg movements, a stiff rear gait, ataxia, and difficulty maintaining equilibrium. From the anterior, kittens appeared bow-legged; however, this also was of neurological origin, and all of these signs were readily reversed by additional threonine. The clinical signs and absence of histopathologic changes in the brain, spinal cord, peripheral nerves, or carpal joints of the deficient cats suggested that the deficiency of threonine induced cerebellar dysfunction.

Requirements and Allowances

Rogers and Morris (1979) and Titchenal et al. (1980) showed that kittens grew maximally when fed diets containing 7 g threonine·kg^{-1} diet. In more extensive experiments in which various concentrations of dietary crude protein were fed, Hammer et al. (1996a) found that, when crude protein was optimal, using growth and nitrogen retention as the variables, the threonine requirement was 6.0 g·kg^{-1} diet containing about 4.6 kcal ME·g^{-1}. Thus, the MR is taken as 5.2 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}. The concentration of threonine in commercial, dry, expanded diets and various purified diets with which normal, sustained growth has routinely been observed is 10.8 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Adverse Effects of Excess Consumption

There are no reports of clinical signs of acute or chronic toxicity related to feeding large quantities of free threonine to cats. Taylor et al. (1998) gave a diet containing 57 g·kg^{-1} threonine (about 4.5 kcal ME·kg^{-1} diet) to kittens (i.e., about nine times the requirement for optimal growth), without any observable adverse clinical signs and with plasma threonine often exceeding 1.5 mmol·L^{-1}. Thus, the SUL for threonine is >51 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Tryptophan

Tryptophan has unique precursor functions besides being needed for protein synthesis. Tryptophan is a precursor of niacin in dogs, and indeed dogs were important as an animal model for solving the problem of pellagra in humans during the early part of the last century (Elvehjem et al., 1937; Krehl, 1981). The cat cannot make significant quantities of niacin from tryptophan as the dog can, primarily because the concentration of picolinic carboxylase is sufficiently high in cats to allow this pathway to predominate rather than the pathway to niacin; the latter pathway, although it exists in the cat, has activities too low to compete effectively with the oxidation pathway (Ikeda et al., 1965). Although tryptophan dioxygenase is up-regulated in cats similar to that in omnivores after administration of tryptophan, this enzyme is not induced by glucocorticoids in cats as in omnivores (Leklem et al., 1969). Tryptophan is also the precursor of the neurotransmitters 5-hydroxytryptophan, serotonin, and melatonin. Plasma tryptophan is usually rather tightly regulated so that there is a sufficient quantity for protein and neurotransmitter syntheses but not an amount that would result in the synthesis of excess neurotransmitters. Plasma concentration of tryptophan in most species is homeostatically controlled by up- and down-regulation of tryptophan dioxygenase, which has a short half-life and can respond quickly, within the absorptive period of a single meal. This short half-life provides for oxidation of excess tryptophan, but prevents the degradation of tryptophan when it is needed for protein or neurotransmitter synthesis. There are indications that dietary supplementation with high concentrations of tryptophan may have some neurobehavioral effects, such as reduced aggression in dogs (DeNapoli et al., 2000), presumably by increasing neurotransmitter synthesis.

Dogs

Signs of Deficiency

Immature beagles fed a tryptophan-free diet exhibited a marked depression in food intake and lost about 29 g BW·d^{-1}, which is similar to the loss when other diets devoid of an essential amino acid were fed (Milner, 1979a,b). No specific clinical signs were reported at the end of the 14-day experiment.

Requirements and Allowances

Weight gain of immature beagles was depressed about 75 percent when tryptophan concentration was decreased from 1.75 to 0.88 g·kg^{-1} diet (Milner, 1979b). Burns and Milner (1982), using 7-week-old beagles in a tryptophan-response experiment, showed a breakpoint for tryptophan for maximal nitrogen retention at 1.5 g·kg^{-1} diet (MR) containing about 4.0 kcal ME·g^{-1}. Czarnecki and Baker (1982), using weight gain of English pointer puppies fed a 162-g amino acid mixture per kilogram of diet, found that the requirement of 6- to 10-week-old puppies was 1.6 g tryptophan or greater, and for 12- to 14-week-old puppies, 1.2 g tryptophan, per kilogram of diet. Since the beagles were fed only about 140 CP·kg^{-1} diet and the pointers about 150 g and the crude protein requirement for 6- to 12-week-old puppies is about 180 g, 1.8-g tryptophan·kg^{-1} diet is taken as the MR for 4- to 14-week-old puppies and 1.4 g tryptophan·kg^{-1} diet for 14-week-old puppies ingesting diets containing 4.0 kcal ME·g^{-1} diet. The concentration in commercial, dry, expanded diets and various purified diets with which normal, sustained growth has routinely been observed is 2.2 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Adverse Effects of Excess Consumption

No reports could be found on acute or chronic toxicity related to feeding large quantities of free tryptophan to dogs fed complete, balanced diets, so no SUL can be established.

Cats

Signs of Deficiency

Removal of tryptophan from the diet of kittens results in a depression in food intake and a weight loss of about 13 g·d^{-1} (Rogers and Morris, 1979). No other signs of deficiency have been reported; nor has long-term deficiency been studied.

Requirements and Allowances

Anderson et al. (1980b) obtained maximal weight gains in kittens given a 186-g amino acid·kg^{-1} diet containing 1.5 g tryptophan·kg^{-1} (4.7 kcal ME·g^{-1}), but they grew at only half that rate when fed 1 g·kg^{-1} diet. Hargrove et al. (1983), using smaller intervals and 240-g amino acid·kg^{-1} diet, reported breakpoints for weight gain and nitrogen retention at 1.1 g tryptophan·kg^{-1} diet (4.7 kcal ME·g^{-1}). Somewhat later, Rogers et al. (1987) showed that increasing the ratio of essential amino acids to dispensable amino acids decreased the crude protein requirement, and that 1.5 g tryptophan·kg^{-1} diet enhanced weight gain more than a diet containing 1.1 g·kg^{-1} with the total dietary amino acids at either 230 or 300 g·kg^{-1} diet. Thus, the MR is taken as 1.3 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}. The concentration of tryptophan in com-

mercial, dry, expanded diets and various purified diets with which normal, sustained growth has routinely been observed is 1.9 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Adverse Effects of Excess Consumption

Taylor et al. (1998) fed 15 g·kg^{-1} tryptophan in a diet containing about 4.5 kcal ME·kg^{-1} (i.e., about 10 times the requirement for optimal growth) without any observable adverse clinical signs and with plasma tryptophan increasing only slightly compared to a control diet. Herwill (1994) fed increasing quantities of tryptophan up to 60 g·kg^{-1} diet (4.7 kcal ME·g^{-1}) to cats and found food intake was somewhat decreased when tryptophan was increased from 20 to 40 g·kg^{-1} and was significantly decreased when tryptophan was increased from 40 to 60 g·kg^{-1}. One cat fed 60 g tryptophan·kg^{-1} diet for 42 days died and was found to have severe diffuse tubular degeneration and atrophy, with proteinaceous casts and interstitial fibrosis of the kidney. Thus, the SUL is about 17 g tryptophan·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Valine

Valine is glucogenic; its only known essential role is as a constituent of proteins.

Dogs

Signs of Deficiency

Immature beagles fed a valine-free diet exhibited a marked depression in food intake and lost about 49 g BW·d^{-1} (Milner, 1979a). No specific clinical signs were reported at the end of the 14-day experiment.

Requirements and Allowances

Weight gain of immature beagles was depressed about 55 percent when valine concentration in the diet was decreased from 8.2 to 4.1 g·kg^{-1} (Milner, 1979a). Burns et al. (1984), in a dose-response experiment, showed that both weight gain and nitrogen retention of weanling beagles at 12 weeks of age plateaued for valine at about 4.5 g·kg^{-1} diet containing 4.1 kcal ME·g^{-1}. Since these beagles were fed only about 140 g of crude protein per kilogram of diet and the requirement for 6- to 12-week-old puppies is about 180 g, 4.5 g·kg^{-1} is taken as the MR for 14-week-old puppies and 5.4 g·kg^{-1} (4 kcal ME·g^{-1}) as the MR for 4- to 14-week-old puppies. The concentration of valine in commercial, dry, expanded diets and various purified diets with which normal, sustained growth has routinely been observed is 9.0 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Adverse Effects of Excess Consumption

No reports could be found on acute or chronic toxicity related to feeding large quantities of free valine to dogs, so no SUL can be established.

Cats

Signs of Deficiency

Removal of valine from the diet of kittens resulted in a weight loss of about 6-14 g·d^{-1} (Hardy et al., 1977; Anderson et al., 1980c). No clinical signs other than weight loss were reported when kittens were fed the valine-free diet for less than 2 weeks.

Requirements and Allowances

Hardy et al. (1977) fed weanling kittens diets containing 6 and 18 g valine·kg^{-1} and found that the weight gains and nitrogen retention of the kittens fed the two concentrations were superimposable. Anderson et al. (1980c), using 3 g valine·kg^{-1} increments below 6 g valine·kg^{-1} diet, reported that 6 g valine·kg^{-1} diet (about 4.7 kcal ME·g^{-1}) was sufficient for maximal weight gain of young kittens. Clearly, 6 g valine·kg^{-1} diet is sufficient, but the requirement could be somewhat lower. Thus, at 4 kcal ME·g^{-1}, the MR for valine is 5.1 g· kg^{-1} diet. The concentration in commercial, dry, expanded diets and various purified diets with which normal, sustained growth has routinely been observed is 10 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Adverse Effects of Excess Consumption

There are no reports of acute or chronic toxicity related to feeding large quantities of free valine to cats. Hargrove et al. (1988) fed cats 100 g valine·kg^{-1} diet containing about 180 g of crude protein and 240 g of fat·kg^{-1} without any observable decrease in weight gain or other adverse clinical signs. Thus, the SUL for valine would be >87 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}.

Minimal Requirements and Recommended Allowances for Maintenance

Dogs

Arginine

No data are available from dose-response experiments for the MR of arginine for maintenance for adult dogs. From Burns et al. (1981), the lowest concentration fed to adult dogs above the arginine-free treatment was 2.8 g·kg^{-1} diet and this concentration minimized orotic acid in urine, thus providing the MR. Casein, milk, and wheat contain sufficient arginine if they are fed at adequate crude protein concentrations, and other proteins including other animal by-products, protein concentrates, and cereals would provide an even greater excess.

Methionine and Cyst(e)ine

Methionine is often considered the first limiting amino acid for adult dogs fed soybean and/or rendered meat meals.

For more than 50 years, there have been various reports that supplementing low-protein diets with methionine increased nitrogen retention or decreased the quantity of crude protein required to maintain nitrogen balance (Allison et al., 1947; Kade et al., 1948; Arnold and Schad, 1954; Ward, 1976). Most were short-term experiments, and results indicated that the total sulfur amino acid requirement was in the range of 2-4 $g \cdot kg^{-1}$ diet. Recently, Sanderson et al. (2001) reported a study in which a diet containing 5.2 g total sulfur amino acids per 4,000-kcal diet was fed to beagles for 4 years without any apparent abnormalities, whereas feeding 4.8 g per 4,000 kcal with a higher-fat diet resulted in one dog exhibiting dilated cardiomyopathy as a result of taurine deficiency, which was corrected by taurine supplementation. Thus, the suggested MRs for maintenance are 5.2 g of total sulfur amino acids and 2.6 g of methionine per kilogram of diet containing 4.0 kcal $ME \cdot g^{-1}$. The D-isomer of methionine has been reported to be well utilized (Cho et al., 1980; Burns and Milner, 1981) by the growing puppy and the adult dog, although dose-response studies have not been reported. Utilization of the D-form, from the above-mentioned work, appeared to be 100 percent that of the L-form.

Histidine, Isoleucine, Leucine, Lysine, Phenylalanine and Tyrosine, Threonine, Tryptophan, and Valine

No individual dose-response peer-reviewed reports could be found for the MR of any of these amino acids for dogs for maintenance. Ward (1976) estimated the MR for these amino acids for maintenance, and Sanderson et al. (2001) fed a low-protein diet to adult dogs for 4 years without any observable clinical signs of deficiency. The lowest dietary concentrations of these two groups are used to estimate the minimum requirements for maintenance and are listed in Table 15-5. No diet that meets the crude protein requirement of dogs at maintenance and includes cereals, animal by-products, and plant protein concentrates has been shown to be deficient in histidine, isoleucine, leucine, phenylalanine and tyrosine, threonine, or valine. Some commercial diets have anecdotally been associated with reddish-brown hair coat in black dogs. No dose-response studies relating phenylalanine and tyrosine to reddish-brown hair in black dogs have been reported in adult dogs. Lysine can be limiting when a cereal protein is fed at the nitrogen requirement, and tryptophan may be limiting when corn and high-collagen diets are used as protein sources.

Cats

Lysine

From the results of a dose-response experiment with adult cats, Burger and Smith (1987) used regression analysis to determine the requirement of lysine at maintenance and reported an MR for lysine for maintenance equivalent to 3 $g \cdot kg^{-1}$ diet containing 4.5 kcal $ME \cdot g^{-1}$. Thus, the MR for lysine for maintenance is set at 2.7 $g \cdot kg^{-1}$ diet containing 4.0 kcal $ME \cdot g^{-1}$.

Methionine and Cyst(e)ine

Burger and Smith (1987) also reported that the methionine requirement for maintenance of nitrogen balance in a diet lacking cyst(e)ine for the adult cat was 3 $g \cdot kg^{-1}$ diet containing 4.5 kcal $ME \cdot g^{-1}$. Thus, the MR for total sulfur amino acids for maintenance is set at 2.7 $g \cdot kg^{-1}$ diet containing 4.0 kcal $ME \cdot g^{-1}$.

Arginine, Histidine, Isoleucine, Leucine, Phenylalanine and Tyrosine, Threonine, Tryptophan, and Valine

No reports of dose-response experiments could be found for the MR of these amino acids for maintenance of adult cats. Since the quantity of these amino acids in the digestible protein in both commercial, dry, expanded diets and purified diets containing 200 g crude protein per kilogram of diet that support maintenance (Piechota et al., 1995) all exceed known MRs for the growing kitten, the MRs for growth for each of these amino acids are taken as the AIs and RAs and reported in Table 15-12.

Minimal Requirements and Recommended Allowances for Gestation and Lactation

Dogs

Arginine, Histidine, Isoleucine, Leucine, Lysine, Methionine and Cyst(e)ine, Phenylalanine and Tyrosine, Threonine, Tryptophan, and Valine

No reports could be found in which the amino acid requirements of the bitch for gestation and lactation have been determined, so no MRs could be estimated. Therefore, the lowest concentrations of each of the essential amino acids from digestible protein in commercial, dry, expanded diets that have been shown to sustain normal gestation and lactation for bitches are taken as the AIs and RAs for gestation and lactation for these amino acids (Table 15-8).

Cats

Arginine, Histidine, Isoleucine, Leucine, Lysine, Methionine and Cyst(e)ine, Phenylalanine and Tyrosine, Threonine, Tryptophan, and Valine

No reports of dose-response experiments could be found for the MR of any essential amino acids for gestation or lactation of adult cats. The AIs, based on the quantity in commercial, dry, expanded diets and various purified diets known to support gestation and lactation (Piechota et al., 1995) for each of the amino acids are shown in Table 15-14.

Dispensable Amino Acids

Dispensable amino acids are good sources of nitrogen in all species including dogs and cats. Although none of the individual dispensable amino acids have been shown to be necessary for any life stage, plasma concentrations of proline and asparagine decreased markedly in growing kittens when they were absent from the diet (Taylor et al., 1996), but growth was not affected. The effect of deleting any one of the dispensable amino acids during gestation and lactation has not been studied; so, it seems prudent to include a mixture of dispensable amino acids in dog and cat diets to supply nitrogen for these life stages. Likewise, excesses of most of the dispensable amino acids have not been studied; so, SUL values cannot be given for any but glutamic acid. Glutamic acid is a central intermediate in amino acid metabolism and is often given as a nitrogen source when free amino acid diets are used in animal research. Generally, it has been shown to be well tolerated. Deady et al. (1981a), in a dose-response study using growing kittens, reported that some emesis occurred, with an associated decrease in weight gain beginning at about 90 g glutamic acid·kg^{-1} diet containing about 4.7 kcal ME·g^{-1}. Thus, the SUL of glutamic acid for the growth of kittens is 75 g·kg^{-1} diet containing 4.0 kcal ME·g^{-1}. It should be noted that the excess glutamic acid caused a thiamin deficiency when thiamin was adequate but marginal in the diet of growing kittens (Deady et al., 1981b). The mechanism by which high dietary glutamic acid increases the thiamin requirement is not known. The SUL for glutamic acid or other dispensable amino acids for dogs is not known.

Taurine

Taurine is a β-aminosulfonic acid (2-aminoethanesulfonic acid), an essential dietary nutrient for cats but dispensable for dogs fed adequate quantities of sulfur-containing amino acids. Taurine is one of the most abundant free amino acids in mammals, being particularly high in brain, heart, and skeletal muscle. Peak concentrations of taurine occur in the total body of newborns and in neonatal brain and gradually decrease by 75 percent as cats mature, but 10 mmol taurine·kg^{-1} is maintained in several tissues in adult cats (Sturman, 1988). Highest concentrations occur in the olfactory bulb and optic nerve. Quantitatively, the major reaction of taurine is its conjugation with bile acids in the liver, but it is also involved in conjugation with a number of compounds to increase their hydrophilic properties for excretion (e.g.; xenobiotics [James et al., 1971; Emudianughe et al., 1983] and vitamin A [Skare et al., 1982]). Taurine is present in a variety of other compounds such as quinaldylglycyltaurine (Kaihara and Price, 1961), guanidotaurine (Thoai and Robin, 1954; Schram and Crokaert, 1957), and γ-L-glutamyltaurine (Furka et al., 1980) in which its functions are poorly understood. Since taurine does not contain a carboxyl group and is a β-amino acid, it is not found in proteins and is made in most species from cysteine. The synthesis of taurine appears to be severely limiting for strict carnivores, but not for most herbivores or omnivores (Chesney, 1985). Taurine is found abundantly in many fish, birds, and small rodents and at lower concentrations in larger species such as bovines, despite first being isolated from ox (*Bos taurus*) bile (Demarcay, 1838). It is present in high concentrations in algae (Reynoso and De Gamboa, 1982), but absent or present only in trace quantities in bacteria and higher plants. Thus, strict vegetarian diets are commonly deficient in taurine. However, crystalline taurine is readily available for supplementing these diets. Taurine deficiency causes a multitude of metabolic aberrations and clinical signs. Taurine is involved in fetal development, growth, reproduction, neuromodulation, sight, hearing, heart function, osmoregulation, fat emulsification, neutrophil function, immune response, antioxidation, and bile acid and xenobiotic conjugation and acts as an anticonvulsant (Huxtable, 1992).

Dogs

Signs of Deficiency

The most common clinical sign of taurine deficiency in dogs has been dilated cardiomyopathy (DCM) (Gavaghan and Kittleson, 1997; Pion et al., 1998; Sanderson et al., 2001; Fascetti et al., 2003). However, it has been reported that some dogs with low plasma taurine also have bilaterally symmetrical hyperreflective retinal lesions, which is similar to classic feline central retinal degeneration (FCRD) (Pion et al., 1998), and poor reproduction has been reported anecdotally in Newfoundlands that had low plasma and whole-blood taurine concentrations (Backus et al., 2003). The occurrence of central retinal lesions together with DCM in dogs seems to be the exception. Whether this represents a species difference or a relative infrequency of retinal examination in dogs is unknown. The incidence of retinal lesions might be higher if the taurine deficiency were more severe. Most dogs with low plasma taurine concentration were large breed dogs fed a diet based on lamb and rice (Backus et al., 2003; Fascetti et al., 2003). Rice bran increases the requirement for taurine in cats (Stratton-Phelps et al., 2002), apparently by binding taurocholic acid and carrying it out in feces or by supporting a bacterial flora that cleaves taurocholic acid and metabolizes free taurine. Since some preparations of lamb meal have very low bioavailabilities of sulfur amino acids (Johnson et al., 1998), a combination of factors could induce taurine deficiency in dogs. Dietary taurine is essential for the fox (Moise et al., 1991), and there are breed differences in dogs susceptibility to DCM and probably also to taurine deficiency (Kramer et al., 1995; Kittleson et al., 1997; Pion et al., 1998; Freeman et al., 2001; Sleeper et al., 2002); however, the roles of genetics, environmental factors, and nutrition have not been fully clarified.

Requirements and Allowances

No reports could be found of dose-response experiments with taurine for dogs fed diets that cause taurine deficiency. Normal dogs make ample taurine from dietary sulfur amino acids via cysteine dioxygenase and cysteinesulfinic acid decarboxylase by conversion to hypotaurine then oxidation to taurine. Thus, dogs fed commercial (Kramer et al., 1995) or purified amino acid diets (Delaney et al., 2001) have normal plasma taurine even if there is no taurine in the diet, and dogs fed these types of diets show no signs of taurine deficiency throughout life. Thus, the MR for taurine for dogs fed a normal diet is 0. Eutaurine status, however, is dependent on an adequate supply of dietary sulfur amino acids; so, with low-protein (Sanderson et al., 2001), low-sulfur amino acid diets or if sulfur amino acids are poorly available (Backus et al., 2003), dogs can become deficient in taurine and exhibit the primary clinical signs of dilated cardiomyopathy (Gavaghan and Kittleson, 1997; Pion et al., 1998; Sanderson et al., 2001; Fascetti et al., 2003), poor reproduction (Backus et al., 2003), and retinal degeneration (Pion et al., 1998). Daily supplements of methionine, without changing the diet, results in an increase in plasma taurine concentration (Backus et al., 2003). It is common for commercial companies that sell low-protein diets to add about 1,000 mg taurine·kg^{-1} diet (DM), which appears to maintain body taurine pools; so, this value is suggested for the AI for diets low in protein or known to be low in sulfur amino acids.

Adverse Effects of Excess Consumption

No reports could be found on acute or chronic toxicity related to feeding large quantities of free taurine to dogs, so no SUL can be established.

Cats

Signs of Deficiency

Taurine deficiency in cats results in FCRD and blindness; DCM and heart failure; inadequate immune response; poor neonatal growth; reduced auditory brain stem evoked potentials resulting in deafness; poor reproduction resulting in a low number of fetuses, resorptions, abortions, decreased birth weight, and low survival rate of kittens; and congenital defects including hydrocephalus and anencephaly.

Hayes et al. (1975a) were the first to report that FCRD was caused by taurine deficiency in cats fed purified diets that contained no taurine. For some time before this report, FCRD had been observed in cats, both clinically (Rubin, 1963; Bellhorn et al., 1974) and in laboratory cats fed casein as the sole dietary protein source (Scott, 1964; Morris, 1965; Rabin et al., 1973). FCRD was also reported in cats fed dog food (Aguirre, 1978). A taurine-free diet fed to cats will produce FCRD with a slight reduction in cone and rod electroretinogram (ERG) a-wave and b-wave amplitudes and delays in the temporal aspects of the cone system b-wave (Hayes et al., 1975b) in as little as 6 weeks. As early as 4 months, after initiation of a taurine-deficient diet, bilateral hyperreflective spots appear in the outer segment of the area centralis in the retina (Anderson et al., 1979b). As the lesions progress, they appear in the outer nuclear layer and outer plexiform layer and are most severe in the area centralis, extending to the periphery. This results in degeneration of that area, which appears as large ellipsoidal lesions, progressing to complete degeneration of the photoreceptor cells, eventually spreading as a generalized atrophy to the entire retina and resulting in blindness. More recently, Leon et al. (1995) showed that in advanced cases of FCRD, regional lesions extended circumferentially to form a peripheral annular band-like arrangement around the retinal extremity, with the circumferential annulus being confluent with both temporal and nasal extremes of the horizontal band-shaped lesion. They reported sclerad displacement of photoreceptor cells into the subretinal space as a common feature.

Pion et al. (1987) was the first to report the association of DCM with taurine deficiency. Dilated cardiomyopathy in cats is characterized by clinical signs rather common for various kinds of heart diseases (Pion, 1989; Pion et al., 1989) such as dehydration, lethargy, and hypothermia, which are most often overlooked by cat owners before an apparent sudden onset of severe dyspnea. Cats with DCM have congestive heart failure, which may be associated with abnormal cardiac sounds or rhythm. Cats with DCM have enlarged hearts with thin walls that weaken the contractibility and thereby lead to inadequate cardiac output, resulting in congestion or edema. Echocardiographs reveal increased end-systolic and diastolic dimensions, especially of the left ventricle, with a marked decrease in shortening fraction (Pion et al., 1987). The right atrium may also appear enlarged. Since there are no specific histopathological lesions associated with DCM it is thought that the primary problem is biochemical, not structural. The primary biochemical defect has been elusive, but is thought to be concerned with membranes and calcium channels that may be involved in the energetics of cardiocytes. Not all cats that have FCRD have DCM, nor do all cats that have DCM have FCRD; nevertheless, many do have both defects.

Sturman and coworkers have reported many taurine-deficiency-related problems in reproduction of queens (Imaki et al., 1986; Sturman et al., 1986; Sturman, 1988; Sturman and Messing, 1991, 1992; Sturman and Lu, 1997). Overall reproduction is poor in taurine-depleted queens, but no reports are available indicating any problem with fertility in taurine-depleted male cats. Both male and female taurine-depleted cats have normal food intake. Taurine-depleted queens are reported to have greater than normal resorptions, abortions, and stillborns; fewer kittens born alive; lower kitten birth weights; lower growth rates; abnormal hind leg development

and peculiar gait; greater mortality of kittens born alive; thoracic kyphosis; and neurological defects including a greater number of congenital defects such as hydrocephalus and anencephaly (Sturman et al., 1986, 1887). Taurine-deficient queens have lower taurine concentrations in their milk, but the rest of the milk composition appears normal (Sturman et al., 1985, 1986). Dieter et al. (1993) confirmed these effects on reproduction and also reported normal estrus and ovulation in taurine-deficient queens; so, they concluded that the defect in taurine-deficient queens is postovulatory and occurs within the first 10 days after implantation.

Other clinical signs have been reported but are more subtle, such as neurological defects (Sturman et al., 1986, 1987) including hearing deficits (Vallecalle-Sandoval et al., 1991, 1993; Davies et al., 1994), osmoregulatory defects (Trachtman et al., 1988), and malfunction of neutrophils (Marcinkiewicz et al., 2000) and other immunological functions (Schuller-Levis et al., 1990). Thus, it can be seen that taurine deficiency has the potential, either directly or indirectly, to adversely affect nearly every system in the body.

Requirements and Allowances

Since taurine depletion that results in clinical signs usually occurs over months to years, depending on the extent of deficiency, few dose-response experiments have been carried out to determine the requirement (Burger and Barnett, 1982; Sturman and Messing, 1991; Morris and Rogers, 1992), and these were done using purified diets, with primarily casein as the dietary protein. Indeed, for many years, Sturman (1993) gave cats diets containing 500 mg taurine·kg^{-1} diet as their control diet without observing any clinical signs of taurine deficiency. However, they reported a slight improvement in reproduction with higher levels of taurine (Sturman and Messing, 1992). Using purified diets in a 17-month experiment, Morris and Rogers (1992), found that 375 mg·kg^{-1} diet (containing 4.7 ME·kg^{-1} diet) prevented abnormal ERG values that occurred when 250 mg taurine·kg^{-1} diet was fed. From this work, which established normal eye function during growth and maintenance and normal gestation and lactation for cats fed purified diets containing 350-400 g CP·kg^{-1} diet (amino acid diets, or one-half from casein and one-half from soybean protein), the MRs for growth, maintenance, gestation, and lactation are 320, 320, 425, and 425 mg taurine·kg^{-1} diet, respectively, containing 4.0 kcal ME·kg^{-1} diet.

Although these MR values are consistent with the 1986 NRC report and continue to be appropriate for purified diets containing highly digestible proteins (Backus et al., 1998), the finding of Pion et al. (1987) in which cats fed commercial canned products containing 1,400-1,800 mg free taurine·kg^{-1} diet exhibited DCM clearly shows that diet composition has a dramatic effect on dietary taurine need. A decadeof work has resulted in a metabolic explanation (Hickman et al., 1990, 1992a,b,c; Kim et al., 1995, 1996a,b; Backus et al., 1998). First, certain fibers (Gallaher and Schneeman, 1986; Anatharaman-Barr et al., 1994; Stratton-Phelps et al., 2002) and peptides (Sugano et al., 1990) bind taurocholic acid and carry it out with feces, which is similar to the effects of cholestyramine (Morris and Rogers, 1994), preventing enterohepatic reutilization of taurocholic acid. Bile acids are obligatorily conjugated to taurine in the cat (Rabin et al., 1976; Rentschler et al., 1986; Hickman et al., 1992a). Certain fibers and/or undigestible protein (Morris et al., 1995) may result in bacterial overgrowth in the ileum by microbes containing cholylhydrolase and cause cleavage of taurocholic acid to taurine and cholic acid, with subsequent oxidation of taurine by microbes, thus preventing its reutilization (Hickman et al., 1990, 1992a,b,c; Backus et al., 1994; Kim et al., 1996b). This mechanism also appears to involve indigestible peptides and increasing cholecystokinin (CCK) (Backus et al., 1995), which in turn increases bile secretion, resulting in more taurocholic acid being available in the intestine for cleavage by bacterial cholylhydrolase and leads to oxidation of taurine, making it unavailable for enterohepatic reutilization of bile acids. Since cats obligatorily conjugate bile acids with taurine when taurine deficient, a high percentage of free cholic acid is found in bile (Rentschler et al., 1986; Hickman et al., 1992a).

There is no single dietary requirement for taurine; the need depends on diet composition, primarily the type, quantity, and digestibility of protein and fiber. As indicated above, the MR for all stages of life for purified diets containing little fiber and highly digestible protein is about 425 mg·kg^{-1} diet containing 4.0 kcal ME·kg^{-1} diet. Because of the variability of fiber type and concentrations used and of protein concentrations and digestibility, no MR can be determined for commercial diets. However, the AI can be established, based on results after feeding a variety of commercial dry and canned diets and examining either the lack of clinical signs of taurine deficiency or, more commonly, whether a particular diet supports adequate plasma and whole-blood taurine concentrations.

Numerous reports show a decrease in the concentration of taurine in plasma (Schmidt et al., 1976; Anderson et al., 1979b; Barnett and Burger, 1980; O'Donnell et al., 1981; Sturman et al., 1986), whole blood (Morris et al., 1990; Douglass et al., 1991; Trautwein and Hayes, 1991; Messing and Sturman, 1993; Pacioretty et al., 2001), and skeletal muscle (Sturman et al., 1986; Pacioretty et al., 2001) when taurine is low or absent from the diet of cats. Cats fed taurine-free purified diets for 3-6 months or longer commonly have plasma taurine concentration of 1-5 nmol·mL^{-1} (Schmidt et al., 1976; Anderson et al., 1979b; Barnett and Burger, 1980; O'Donnell et al., 1981; Sturman et al., 1986), which is the most rapid body pool to be depleted, except possibly the liver, which uses taurine for conjugation to bile acids. Careful preparation of plasma is required because taurine is particularly high in platelets, granulocytes, and lymphocytes (Laidlaw et al., 1987); thus, partial clotting or con-

tamination of the plasma with white cells can cause false high taurine values for plasma. Using a constant preparation procedure for clotting, Pacioretty et al. (2001) found that normal serum taurine concentration was about twice that of plasma and about half that of whole blood. These ratios increased somewhat as body taurine pools were depleted. Use of serum for determining taurine status is not recommended because the quantity of taurine in serum varies with the procedure and the time allotted for coagulation and retraction of the clot. Sturman and coworkers (1993) and Pacioretty et al. (2001) demonstrated that various body pools are depleted at different rates. Plasma taurine is depleted most rapidly, followed by whole blood, muscle, and finally brain and other nervous tissue. Although taurine concentrations are highest in certain parts of the brain, and heart muscle has a higher concentration than skeletal muscle, it is not normally feasible to obtain heart or neural tissue for clinical evaluation, and muscle biopsies are not routinely obtained. Therefore, plasma and whole-blood taurine concentrations have become the standard variables for use in assessing the taurine status of cats. Whole-blood concentration is preferred, since it provides an indication of longer-term taurine status and contains white cells so that clotting is not a problem (except in subsampling). Eutaurine status in which sufficient taurine is present to provide substantial taurine in the urine supports plasma and whole-blood concentrations of about 100 and 500 nmol·mL^{-1}, respectively (Pacioretty et al., 2001). Minimal safe plasma and whole-blood concentrations (AI) are not unequivocally defined, but 40 and 200 nmol·mL^{-1}, respectively, have been used without any reported problems as minimal safe levels for complying with Association of American Feed Control Officials (AAFCO, 2002) protocols. These concentrations have been used as guidelines by clinicians for a low risk of taurine deficiency causing DCM in cats. It is known that 25 nmol·mL^{-1} in plasma is clearly inadequate (Pion et al., 1987). The use of whole blood for determining taurine status is also recommended because of the effect of time of feeding and food deprivation on plasma taurine. Pion et al. (1991) found that plasma taurine of meal-fed cats fed a purified diet or a dry or canned commercial cat food increased postprandially and then decreased with time of food deprivation up to 71 hours. From these results, it is clear that, if plasma is used to evaluate taurine status, cats should be fed and not food-deprived for a prolonged period. This same group reported that at no time was there any significant difference in whole-blood taurine concentrations among cats fed various diets. This supports the use of whole-blood taurine concentration in determining the taurine status of an animal.

Using clinical data and plasma and whole-blood taurine concentrations as indicated above for assessing commercial, dry, expanded diets, the AI suggested is 1,000 mg taurine·kg^{-1} diet containing 4.0 kcal ME·kg^{-1} (Morris et al., 1990; Earle and Smith, 1991; Morris and Rogers, 1992; Markwell and Earle, 1995) and for commercial, canned diets, 1,700 mg taurine·kg^{-1} diet containing 4.0 kcal ME·kg^{-1} (dry matter) (Morris et al., 1990; Earle and Smith, 1991; Morris and Rogers, 1992; Markwell and Earle, 1995).

Adverse Effects of Excess Consumption

There are no reports of acute or chronic toxicity related to feeding large quantities of free taurine to cats. Sturman and Messing (1992) fed weanling kittens 10 g taurine·kg^{-1} diet containing about 4.5 kcal ME·g^{-1} for up to 3 years and found no adverse effects; thus, the SUL for kittens is >8.9 g·kg^{-1} diet containing 4 kcal ME·g^{-1}.

AMINO ACID IMBALANCES AND ANTAGONISMS

There are few reports of studies on amino acid imbalances and antagonisms in dogs and cats. Omnivores are most sensitive to disproportional quantities of dietary amino acids when fed diets limiting in protein and all of the essential amino acids (Harper et al., 1970). Omnivores and herbivores adapt to high-protein diets by decreasing their food intake and weight gain for 1-5 days (depending on the levels of dietary protein used) and then, after amino acid and nitrogen homeostasis is restored, by up-regulating amino acid and nitrogen catabolic enzymes, normal growth resumes (Harper, 1965; Schimke, 1962; Anderson et al., 1968, 1969). It is clear that cats are much less sensitive to disproportional quantities of dietary amino acids than are rats, chicks, and other herbivores and omnivores (Rogers et al., 1987; Strieker, 1991), probably because the quantity of protein that meets the MR usually carries with it a high percentage of the MR of essential amino acids. Although the metabolic basis of the high crude protein requirement for maintenance is controversial (Rogers and Morris, 2002; Russell et al., 2002), it has been shown consistently that cats will not maintain nitrogen balance at the same low dietary crude protein concentrations that occur for most herbivores and omnivores (Hendriks et al., 1997). It is known that cats do not up- or down-regulate the nitrogen catabolic enzymes to nearly the same extent as omnivores and herbivores (Rogers et al., 1977), so it appears that cats are always adapted to handle a medium to high level of dietary amino acids. This minimizes the adverse effects of disproportional quantities of amino acids.

Only a very minor growth depression occurred in kittens when crude protein was increased in a diet limiting in threonine (Hammer et al., 1996a), whereas Strieker (1991) showed that, even if methionine was limiting, increasing dietary crude protein slightly increased weight gain. Rogers et al. (1987) reported a survey of the effects of increasing crude protein in diets in which an essential amino acid was limited to about 80-90 percent of the requirement for weight gain of kittens. They showed either that there was no effect or that weight gain was improved by the addition of an amino acid mixture to the diet that lacked the limiting amino

acid. Although decreasing the percentage of each amino acid even further may have resulted in an amino acid imbalance, it is clear that cats are less sensitive to such imbalances than omnivores and herbivores. Cats are also insensitive to arginine-lysine antagonisms (Anderson et al., 1979a) and much less sensitive to leucine-isoleucine and -valine antagonism (Hargrove et al., 1988, 1994). Thus, cats transitorily reduced their food intake and growth when excess leucine was added to the diet only if isoleucine was already limiting (Hargrove et al., 1988), and even then, cats would select the high-leucine diet over the more balanced diet (Hargrove et al., 1994). Strieker (1991) found that when methionine was severely limiting (1.6 g·kg^{-1} diet each of methionine and cysteine) although a dietary supplementation of 13.4 g cystine·kg^{-1} did not lead to a further decrease in food intake and growth, it did cause severe pyrodermatitis at the commisures of the mouth and necrolytic dermatosis on the pads of the feet, all of which were rapidly corrected when more methionine was added to the diet.

Metabolic adaptation of amino acid metabolism in dogs indicates that they are intermediate between rats and cats (i.e., there is some up- and down-regulation of amino acid and nitrogen catabolic enzymes but not to the same extent as found in rats; Morris et al., 2002). After adaptation, dogs do not maintain plasma amino acids within as narrow a range (Torres and Rogers, 2002) as rats (Anderson et al., 1969). Over the short term, dogs can maintain nitrogen balance at nearly as low a crude protein concentration as rats (Melnick and Cowgill, 1937; Kade et al., 1948; Arnold and Schad, 1954), and indeed, in sporadic reports during the past 50 years, results indicate that dogs show amino acid imbalances and antagonisms more similar to those of rats. Gessert and Phillips (1956) reported that when 4 g lysine·kg^{-1} was added to a low-protein basal diet, apparently limiting in sulfur amino acids, weight gain was depressed 28 percent and was restored by the further addition of 3 g DL-methionine·kg^{-1} diet. In a second experiment with a different basal diet apparently limiting in lysine, they showed that 1.5 g methionine·kg^{-1} diet depressed weight gain 37 percent, which was restored by the addition of 1.3 g lysine·kg^{-1} diet. They concluded that the depressions in weight gain were the result of amino acid imbalances that fit the general definition of imbalance as defined by Harper et al. (1970). Other reports confirm that amino acid imbalances occur in growing dogs (Bressani, 1963). A lysine-arginine antagonism has been reported in growing dogs by Czarnecki et al. (1985) (i.e., 40 g lysine·kg^{-1} added to a basal diet somewhat limiting in arginine caused a decrease in weight gain that was largely corrected by the addition of 4 g arginine·kg^{-1} diet). This same group (Hirakawa and Baker, 1985) reported that in puppies the addition of 2.2 g cystine·kg^{-1} to a diet severely limiting in methionine (1.1 g·kg^{-1} diet) caused a decrease in weight gain and necrotic skin lesions on the pads of the front feet, which were corrected rapidly when methionine was added to the diet. There have been reports that leucine induces niacin deficiency in dogs fed diets marginal in tryptophan and niacin (Belavady et al., 1967), but these results could not be reproduced in dogs (Manson and Carpenter, 1978) or rats (Nakagawa and Sasaki, 1977). Thus, in general, dogs appear to be more sensitive to disproportionalities among dietary amino acids than cats, especially when fed low-protein diets.

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7

Minerals

INTRODUCTION

Experimental evidence is available for the essentiality of some 11 minerals in dogs and cats. Several others are assumed to be essential, due to evidence of their need in other species, and are most likely present in dog and cat foods at concentrations sufficient to meet metabolic needs. The minerals present in a feed are found mainly in the ash component when the feed is analyzed by use of American Organization of Analytical Chemists (AOAC) procedures, which are the methods recommended in the model feed bill of the Association of American Feed Control Officials (AAFCO) for determining the guaranteed analysis of a feedstuff (AOAC, 2000; AAFCO, 2001). The ash consists of oxides, phosphates, carbonates, and sulfates of minerals (inorganic elements) including calcium (Ca), phosphorus (P), magnesium (Mg), sodium (Na), potassium (K), iron (Fe), copper (Cu), manganese (Mn), and zinc (Zn). Other minerals such as chloride (Cl^-), iodine (I), sulfur (S), and selenium (Se) may be partially or totally lost in the form of gaseous compounds during the combustion process.

Several methods have been used for classifying nutritionally essential minerals in feedstuffs. In this discussion, minerals are divided into macrominerals and trace minerals. Macrominerals are those that are usually expressed in grams or fractions of grams per 1,000 kcal of metabolizable energy (ME) or as grams or fractions of grams to one decimal place per kilogram on a dry matter (DM) basis in the diet. These minerals include Ca, P, Mg, Na, K, and Cl^-. Trace minerals consist mainly of those minerals usually expressed in terms of milligrams or fractions of milligrams per 1,000 kcal ME or as milligrams or fractions of milligrams to one decimal place per kilogram on a DM basis in the diet. These minerals include Fe, Zn, Cu, Mn, I, and Se as well as those that may be required at even lower concentrations in petfoods, such as molybdenum (Mo), boron (B), and chromium (Cr).

Minerals serve many physiological functions in animals. In vertebrates, Ca and P play a vital role in the rigidity of the internal skeleton as well as of teeth. Minerals such as Ca, Mg, K, and Na are also essential for nervous impulse transmission and muscle contraction, and they have many second messenger and cell signaling functions, as well as playing a vital role in maintaining the acid-base balance of the organism. In addition to its role in the skeleton, P is an essential component of cellular and subcellular membranes and is a crucial component in energy metabolism. It also plays an important role in DNA and RNA metabolism. The primary roles of many minerals, especially trace minerals (e.g., Se, Cu, Mo), are in metalloenzymes where they function in a multitude of enzymatic reactions. Minerals such as Fe, Zn, and I play essential roles in protein and hormone structure and/or function.

Nutritional deficiencies of many essential minerals have been produced experimentally, and clinical signs have been described. Many such deficiencies can also occur as clinical problems in dogs and cats, particularly those fed improperly formulated home-prepared diets. Additionally, some minerals whose presence in the diet is essential for the health of dogs and cats may cause clinical abnormalities when consumed in excess.

MINERALS AND ACID-BASE BALANCE

The composition of the diet and nutrient metabolism have significant effects on the generation of acids and bases whose physiological concentrations, under normal conditions, are controlled by the respiratory and renal systems (Toto et al., 1996). Catabolism of sulfur-containing amino acids results in hydrogen ion release in conjunction with the production of sulfate anions. Cellular metabolism of neutral phosphoproteins and phospholipids yields hydrogen ions when negatively charged phosphate residues are neutralized by hydrogen ions or cationic amino groups (Toto et al., 1996). The metabolism of various dietary organic cations and anions may liberate acid and base, respectively, and mineral absorption from the intestine may also result in the

addition of acid or base to the internal milieu, depending on the amount and composition of the mineral salts consumed (Lennon et al., 1966; Lemann and Lennon, 1972; Toto et al., 1996). Protein metabolism can also result in the generation of ammonia, which can contribute to urinary acid excretion. The net amount of acid added to the extracellular fluid from the diet or from bone is referred to as endogenous acid production (EAP), which can be either a positive or a negative number (Lemann and Lennon, 1972). Additionally, under the conditions of physiological steady state, this will relate directly to net urinary acid excretion (NAE) (Zijlstra et al., 1995; Toto et al., 1996). Thus, the amount of acid excreted in the urine, reflected by urinary pH, is directly related to the composition of the diet.

Furthermore, feeding husbandry can have an effect, at least transiently, on acid-base status and NAE. Food consumption, through several mechanisms, causes hydrochloric acid (HCl) to be secreted into the stomach, which assists in the initial steps of food digestion. The amount of HCl secreted is related to stomach fill. The hydrogen ions secreted are produced through the action of carbonic anhydrase, and intracellular Cl^- concentration is preserved by a bicarbonate-chloride exchange mechanism at the basolateral membrane of the parietal cell, adding net bicarbonate to the extracellular fluid. Thus, eating is associated with a relative metabolic alkalosis, which is referred to as the "alkaline tide" (Argenzio, 1984). Compensation includes an increase in urinary bicarbonate excretion, causing a rise in urine pH. For example, cats fed once per day have been shown to have a significant increase in urinary pH for 2 to 12 hours after feeding compared to cats fed free-choice (Taton et al., 1984).

Another player in the maintenance of acid-base balance is bone. In conditions of relative metabolic acidosis, exchangeable bone mineral in the form of calcium carbonate provides a source of buffer (Lemann et al., 1966; Burnell and Teubner, 1971; Toto et al., 1996). The dissolution of exchangeable bone calcium phosphate salts also contributes to this acid buffering capacity (Brosnan and Brosnan, 1982). This buffering action is accompanied by a loss of calcium salts from bone and can lead to osteomalacia in the face of a chronic relative metabolic acidosis (Ching et al., 1989).

In the wild, dogs and cats consume a mainly carnivorous diet, and animal protein sources have higher concentrations of sulfur-containing amino acids than vegetable protein sources (Pennington, 1998). For this reason, in nature dogs and cats have a positive EAP and NAE resulting in an acidic urinary pH (6.0-7.0). The development of commercial petfoods, particularly dry foods, led to the inclusion of significantly greater amounts of vegetable source ingredients as protein and energy sources in the diet of dogs and cats (Coffman, 1995, 1997). This has been associated with increased consumption of organic anions and mineral cations (base-forming elements), which induces a relative metabolic alkalosis, resulting in more alkaline urine.

This is of particular importance in the cat which even under normal circumstances produces a more highly concentrated urine than does the dog or human (Osborne et al., 1995). This may be a factor in the significant incidence of urolithiasis, due mainly to the spontaneous formation of struvite (magnesium ammonium phosphate) uroliths, that was observed in this species in the 1970s and 1980s (Willeberg, 1984; Lawler et al., 1985). A number of studies suggested that a higher than required dietary concentration, and thus a higher than required dietary intake, of Mg was of etiologic significance in the development of this metabolic abnormality (Lewis et al., 1978; Kallfelz et al., 1980; Lewis and Morris, 1984). Subsequently, it was discovered that the Mg effect depended on urinary pH. Cats fed diets inducing an increased NAE and an acidic urinary pH did not develop the problem, while cats fed a ration resulting in alkaline urine did at the same concentrations of dietary Mg (Buffington et al., 1985, 1990). It now appears that formulating cat foods so as to increase NAE and induce a urinary pH of approximately 6.1-6.6 is an effective method of controlling struvite urolithiasis formation in this species, as long as dietary Mg concentrations are not excessive (Allen et al., 1997).

Attempts have been made to estimate urinary pH from the composition of the diet. Such approaches have been based on the concentrations of mineral cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) and anions (phosphate [PO_4^{3-}], sulfate [SO_4^{2-}], and Cl^-) in the diet and subtraction of the anion total from the cation total. These techniques have been variously referred to as dietary anion gap, base excess, or cation-anion difference (Oetzel et al., 1988; Kienzle et al., 1991a; Kienzle and Wilms-Eilers, 1994; Toto et al., 1996). A positive value reflects a net excess of alkalinizing anions, while a negative value reflects a net excess of acidifying cations in the diet. A close correlation has been shown between the base excess of cat foods and the pH of urine. Diets with base excesses between –400 and –800 $mmol \cdot kg^{-1}$ dry diet have been shown to produce average daily urine pHs between 6.6 and 6.2 (Kienzle et al., 1991a; Kienzle and Wilms-Eilers, 1994).

While reducing dietary Mg concentration and urinary pH has greatly reduced the incidence of struvite urolithiasis in cats, it has not eliminated the problem of urolithiasis or other forms of lower urinary tract disease (LUTD) in this species. For example, a specific cause cannot be identified in a significant fraction of cats with LUTD (Kruger et al., 1991). Even so, nonobstructive LUTD does appear to be more prevalent in cats fed dry cat food (Buffington et al., 1997). Further, it has been reported that the feeding of a canned, as opposed to dry, diet which induces an acid urine may be helpful in the management of idiopathic cystitis (Markwell et al., 1999). While there is some evidence that consumption of a canned, as opposed to dry, diet has little effect on total water intake or urinary water output in cats, the preponderance of evidence suggests that eating canned

diets does result in a greater total water intake by cats compared to consumption of a dry diet (Sauer et al., 1985).

Another observation has been that as the incidence of feline struvite urolithiasis has decreased, the incidence of calcium oxalate urolithiasis has increased (Osborne et al., 1996). The etiologic significance of dietary factors in calcium oxalate urolithiasis is, however, unknown. Dietary manipulations to increase NAE may increase urinary Ca excretion (Ching et al., 1989). This, as well as the more highly concentrated urine normally produced by the cat as compared to the dog, could promote calcium oxalate formation (Osborne et al., 1995). The ingredients used in commercial cat foods do not contain significant amounts of oxalate. While experimentally induced pyridoxine deficiency in kittens results in increased urinary oxalate excretion, which may cause nephrocalcinosis, this has not been seen clinically. Further, pyridoxine supplementation does not decrease urinary excretion of oxalate (Gershoff et al., 1959; Bai et al., 1989). The relationship of dietary factors to calcium oxalate urolithiasis in cats, and also in dogs, deserves further study.

MACROMINERALS

The mineral content of common petfood ingredients is listed in Table 13-5.

Calcium

The mineral element found in the greatest abundance in mammals, including dogs and cats, is Ca (Kienzle et al., 1991b, 1998b; Lobaugh, 1996). Using total carcass analysis, Kienzle et al. (1998b) found that at birth puppies contain close to 6 g $Ca \cdot kg^{-1}$ of body weight (BW), which increases to about 12 g $\cdot kg\ BW^{-1}$ in adults. For cats, the values are about the same at birth but are somewhat higher, about 15 g $\cdot kg\ BW^{-1}$, in adults (Kienzle et al., 1991b). In terms of Ca requirements, the greatest need occurs during the period of active formation of bones and teeth. However, Ca plays several other vital roles in physiology and metabolism, although such actions require several orders of magnitude lower amounts or concentrations of Ca than that required for bone and tooth health. For example, Ca plays essential roles in blood coagulation, nerve impulse transmission, excitation contraction coupling, and muscular contraction, and it serves as a second messenger in a host of intracellular reactions.

There are various dietary sources of Ca. Dairy products such as milk and cheese are generally good sources. Some vegetables such as broccoli and cabbage are also reasonable sources (Pennington, 1998). Alfalfa is an excellent source of Ca for herbivores. However, none of these are common ingredients in dog and cat foods. Sources of Ca commonly used in petfood products include meat and bone meal, 10 percent Ca; bone meal, 31.0 percent Ca; dibasic calcium phosphate, 22 percent Ca; monobasic calcium phosphate, 16.4 percent Ca; and calcium carbonate, 39.4 percent Ca (Tables 13-6 and 13-8).

Absorption and Bioavailability of Dietary Calcium in Dogs

A uniform estimate of bioavailability is desirable to establish minimum dietary Ca concentrations in petfoods. However, as was true more than half a century ago, this is difficult if not impossible to determine since factors such as life stage, breed differences, and other dietary constituents modify the need for and bioavailability of Ca (McCay, 1949). Gershof et al. (1958) estimated the apparent absorption of ingested Ca in 8- to 12-week-old mongrel puppies fed a purified dry diet as 90, 46, and 27 percent for diets containing an estimated 1.3, 7.0, or 13.7 g $Ca \cdot kg^{-1}$ as calcium carbonate, DM basis, respectively. Hedhammar et al. (1980) found apparent absorption of dietary Ca ranging from 0 to 85 percent in 8-week-old German shepherd puppies fed dry diets (90 percent DM) with Ca concentrations of 11.1-15.6 g $\cdot kg^{-1}$ DM or frozen diets (30 percent DM) containing 8.3-25.0 g $Ca \cdot kg^{-1}$ DM basis, the source of the Ca in these studies being unreported. More recently, using kinetic analysis, true absorption percentages of 70-99, 28-53, and 37-50 were observed in 13- to 25-week-old miniature poodle puppies fed dry diets containing 0.5 or 3.3, 11.0, and 33.0 g $Ca \cdot kg^{-1}$ respectively as mixtures of almost equal amounts of calcium carbonate and dicalcium phosphate (Nap et al., 1993). In Great Dane puppies 14 to 26 weeks of age, Hazewinkel et al. (1991) found true Ca absorption of 70-97, 45-66, and 23-43 percent when dry type diets containing 5.5, 11, or 33 g $Ca \cdot kg^{-1}$ as a mixture of monocalcium phosphate and calcium carbonate, DM basis, were fed. Dietary P concentration (5 or 9 g $\cdot kg^{-1}$) did not affect Ca absorption in this study (Hazewinkel et al., 1991). Similar true absorptions were found by Schoenmakers et al. (1999) in Great Dane puppies 9- to 15-weeks-old that were fed dry type diets containing 10.4 or 31 g $Ca \cdot kg^{-1}$ also as a mixture of monocalcium phosphate and calcium carbonate, DM basis.

In adult dogs, Hedhammar et al. (1980) reported apparent Ca absorptions of 30-50 percent and close to 100 percent in Golden retrievers fed dry type diets containing 14 g or 1.1 g $Ca \cdot kg^{-1}$, DM basis, the source of the Ca not being reported. Chanard et al. (1980) observed true Ca absorption averaging 27 percent in 15 to 25 kg adult mongrel dogs fed a commercial diet containing 13 g $Ca \cdot kg^{-1}$, DM basis. Beynen et al. (2001) measured an apparent absorption of ingested Ca averaging 11.5 percent in six adult dogs weighing 12 to 17 kg fed a commercial moist diet (35.1 percent moisture) containing 8.5 g $Ca \cdot kg^{-1}$, DM basis. From intake and other data, the true absorption rate can be estimated at approximately 30 percent. In another study of young adult (1-year-old) and geriatric (10-year-old) beagle dogs fed commercial diets containing approximately 17 g $Ca \cdot kg^{-1}$ (1.7 percent), Sheffy et al. (1985) observed apparent absorptions of 27.4 percent and 26.9 percent, respectively. There was no significant dif-

ference in apparent absorption between the two age groups (Sheffy et al., 1985). More recently, net apparent absorption of Ca was found to be indistinguishable from 0 percent when adult hound dogs were fed standard-type diets containing 20 g $Ca \cdot kg^{-1}$ as calcium phosphate, DM basis, with various amounts of beef and soy as the protein source (Hill et al., 2001).

Based on the above, there appears to be sufficient evidence that in dogs, Ca availability decreases during the growth period and also with increasing dietary Ca concentration. Hoff-Jorgensen (1945) reported that the presence of phytate in plant material reduced Ca bioavailability in canine diets, but there are few recent data on this effect in dogs or cats. Recent measured absorption percentages of Ca in dogs are likely to be reasonable since the dry diets used were similar, though not identical, in composition to contemporary commercial dry dog foods (Chanard et al., 1980; Hazewinkel et al., 1991; Nap et al., 1993; Beynen et al., 2001). There is also evidence that feeding diets resulting in a decrease in pH of the distal small intestine and colon are associated with higher absorption percentages of Ca (Beynen et al., 2001, 2002). The dietary Ca:P ratio is another factor that may affect the absorption of Ca. However, given reasonable concentrations of both minerals in the diet, recent studies suggest that this does not have a significant effect on Ca absorption (Hazewinkel et al., 1991; Nap et al., 1993). Although increasing dietary fat concentrations have been suspected to decrease Ca absorption, Jenkins and Phillips (1960b) found similar apparent absorption of Ca from diets containing 3 or 20 percent fat. Similarly, Hallebeek and Hazewinkel (1998) found no effect of fat at concentrations of 33 percent compared to 11 percent on Ca absorption in 6-month-old beagle dogs.

Calcium Deficiency in Dogs

A deficiency of dietary Ca results in a condition known as nutritional secondary hyperparathyroidism (NSHP). The reduced input of Ca to extracellular fluid results in a decreased concentration of ionic Ca, which stimulates an increase in the secretion of parathyroid hormone (PTH). The increase in plasma concentration of PTH causes increased production of calcitriol, the most active form of vitamin D, which along with PTH stimulates increased bone resorption as a mechanism for returning the circulating ionic Ca concentration to normal (Potts and Juppner, 1998). Chronic dietary Ca deficiency causes major decreases in bone mineral content, which can result in significant skeletal abnormalities including fractures.

Calcium deficiency resulting in NSHP has been recognized clinically for many years in dogs fed commercial or home-prepared diets consisting mainly of meat. Hazewinkel et al. (1991) described severe signs of nutritional hyperparathyroidism, including pathological fractures, in Great Dane puppies fed dry diets with Ca concentrations of 5.5 $g \cdot kg^{-1}$, DM basis. The experimental diets were begun when puppies were 8 weeks old, and clinical signs became severe at approximately 5 months of age. Calcium intakes varied between 250 and 150 mg·kg $BW^{-1} \cdot d^{-1}$ during the 18-week experiment, with true absorptions varying between 95 percent and 75 percent, respectively (Voorhout and Hazewinkel, 1987; Hazewinkel et al., 1991). Similarly, Goodman et al. (1998) and Lauten and Goodman (1998) demonstrated a slower growth rate and a slight relative osteomalacia in Great Dane puppies fed diets containing 1.2 g Ca per 1,000 kcal ME compared to dogs fed diets with higher concentrations of Ca (Goodman et al., 1998; Lauten and Goodman, 1998). More recently, Laflamme (2000) reported slow growth and decreased feed efficiency in puppies of several medium- to large-sized breeds, including English setters, German shepherds, Labrador retrievers, and huskies, as a result of feeding diets containing an average of 2.2 g Ca per 1,000 kcal for a period of 5 to 10 weeks. Neither the age nor the weight of the puppies used was reported. No skeletal pathology was observed in these studies (Laflamme, 2000).

No abnormalities were reported in miniature poodle puppies (13 to 25 weeks of age) fed similar diets with a Ca concentration of 3.3 g $Ca \cdot kg^{-1}$ diet, DM basis, corresponding to a Ca intake of 140 mg·kg $BW^{-1} \cdot d^{-1}$ (Nap et al., 1993). In the same experiment, feeding a diet containing 500 mg $Ca \cdot kg^{-1}$ diet did result in signs of nutritional hyperparathyroidism. However, Gershoff et al. (1958) found no abnormalities in mongrel dogs fed for more than 2.5 years, beginning at an age of 2 months, a purified diet containing an estimated 1.3 g $Ca \cdot kg^{-1}$ diet, DM basis. The apparent absorption of Ca was 90 percent in this study, which may be higher than would ordinarily be expected from standard-type diets.

Henrikson (1968) and Krook et al. (1971) observed significant skeletal abnormalities in adult beagle dogs fed a diet containing 1.2 g versus 12 g $Ca \cdot kg^{-1}$ diet, DM basis. However, Hedhammar et al. (1980) reported only a transient decrease in mineral content of bone in adult Golden retrievers fed a dry diet containing only 1 g $Ca \cdot kg^{-1}$ diet, providing a Ca intake of 20 mg·kg $BW^{-1} \cdot d^{-1}$. True Ca absorption of close to 100 percent was reported in this study. These results support those of Gershoff et al. (1958) who found that dogs could maintain Ca balance when fed a purified diet containing an estimated 1.3 g $Ca \cdot kg^{-1}$, DM basis.

Adverse Effects of Excessive Consumption of Calcium in Dogs

Excessive Ca intake has also been found to result in significant skeletal abnormalities, particularly in growing puppies of giant breeds (Hedhammar et al., 1974; Hazewinkel et al., 1985, 1991; Goedegebuure and Hazewinkel, 1986; Voorhout and Hazewinkel, 1987). Free-choice-fed Great Dane puppies fed a diet containing 20.4 g $Ca \cdot kg^{-1}$ (5.2 g per 1,000 kcal ME) consuming from 1,374 mg Ca·kg $BW^{-1} \cdot d^{-1}$

to 362 mg·kg $BW^{-1}·d^{-1}$ as they grew to just over 1 year of age developed clinical and pathological skeletal changes including osteochondrosis, decreased bone turnover, and increased bone mineral content compared to restricted fed animals (1,057-362 mg·kg $BW^{-1}·d^{-1}$) that developed normally (Hedhammar et al., 1974). Great Dane puppies fed a diet containing 33 g $Ca·kg^{-1}$, DM basis, developed osteochondrosis, radius curvus, and stunted growth (Hazewinkel et al., 1985).

Using kinetic approaches, Hazewinkel et al. (1991) demonstrated decreased percentage intestinal Ca absorption, increased total Ca absorption, decreased bone turnover rates, and similar pathological changes in growing Great Dane puppies fed diets containing 8.9 g Ca per 1,000 kcal ME, 33 g $Ca·kg^{-1}$ diet, and 3,700 kcal $ME·kg^{-1}$, DM basis. These puppies consumed 960-1,400 mg Ca·kg $BW^{-1}·d^{-1}$, compared to litter mates fed a diet containing 3.0 g Ca per 1,000 kcal ME, 11 g $Ca·kg^{-1}$ diet, that consumed 300-460 mg Ca·kg $BW^{-1}·d^{-1}$ (Voorhout and Hazewinkel, 1987; Hazewinkel et al. 1991). Nap et al. (1993) fed similar diets to miniature poodle puppies, causing similar changes in Ca metabolism to those observed in large-breed puppies; however, no significant skeletal abnormalities were observed.

Goodman et al. (1998) and Lauten and Goodman (1998) also reported poor conformation and skeletal lesions in Great Dane puppies fed diets containing 6.8 g Ca per 1,000 kcal ME. In an epidemiologic study, Slater et al. (1992) found that feeding large-breed puppies diets with Ca concentrations of ≥3.6 g per 1,000 kcal ME was associated with an increased risk of osteochondritis. Thus, excess dietary Ca has been shown to cause clinically recognizable bone abnormalities in growing dogs, but these effects appear restricted to puppies of large breeds.

Dietary Calcium Requirements and Allowances in Dogs

Requirements and Allowances for Puppies

The minimum requirement (MR) for Ca varies depending on the breed and age of growing puppies. Hazewinkel et al. (1991) found that standard diets containing 1.5 g Ca per 1,000 kcal ME, providing a Ca intake of 150-250 mg·kg $BW^{-1}·d^{-1}$ and a true absorption of 120-180 mg·kg $BW^{-1}·d^{-1}$, were insufficient to support normal growth in Great Dane puppies, even though true absorption was close to 100 percent. However, diets containing 3.0 g Ca per 1,000 kcal ME with a true absorption percentage of 45-70 percent, providing a true absorption of 200 mg·kg $BW^{-1}·d^{-1}$, supported normal growth. Goodman et al. (1998) and Lauten and Goodman (1998) reported that feeding diets containing 2 g Ca per 1,000 kcal ME (8.2 $g·kg^{-1}$, 4,000 kcal $ME·kg^{-1}$) also supported growth of Great Dane puppies. Laflamme (2000) reported that feeding growing medium- to large-breed puppies diets containing 3.9-5.7 g Ca per 1,000 kcal also resulted in normal growth, while feeding diets providing 2.2-2.6 g per 1,000 kcal ME resulted in poor growth even though no skeletal lesions were observed.

While Nap et al. (1993) found that miniature poodle puppies grew normally when fed basal dry-type diets containing only 0.9 g Ca per 1,000 kcal, DM basis, feeding similar puppies diets containing 3.0 g Ca per 1,000 kcal ME also resulted in normal growth. Based on these observations and those of Goodman et al. (1998) and Lauten and Goodman (1998) mentioned previously, a calcium concentration of 2.0 g Ca per 1,000 kcal ME (8.0 g $Ca·kg^{-1}$, 4,000 kcal $ME·kg^{-1}$) may be set as the MR of dietary Ca that will support normal growth in puppies of both large and small breeds although it will likely exceed MRs in other than giant breeds. Such a diet will provide a daily Ca intake of 370 $mg·kg^{-1}$ (560 mg Ca·kg $BW^{-0.75}·d^{-1}$) for a 5.5-kg puppy consuming 1,000 kcal $ME·d^{-1}$ (Nap et al., 1993; Lauten and Goodman, 1998). Although Laflamme (2000) suggested that this concentration of dietary Ca may not support optimal growth in some large breeds, the diets used in these experiments may have resulted in a lower percentage of Ca absorption than that measured in the former studies since they were standard diets of only moderate caloric density that may have contained ingredients that reduce the absorption of calcium (Hoff-Jorgensen, 1945).

Regarding the recommended allowance (RA) for Ca in puppy diets, the data of Hazewinkel et al. (1991), Schoenmakers et al. (1999), and Nap et al. (1993) suggest that a dietary concentration of 3.0 g Ca per 1,000 kcal ME (12 g $Ca·kg^{-1}$, 4,000 kcal $ME·kg^{-1}$) should be sufficient for all breeds. Such a diet would provide a Ca intake of 545 mg·kg $BW^{-1}·d^{-1}$ (680 mg Ca·kg $BW^{-0.75}·d^{-1}$) for a 5.5-kg puppy consuming 1,000 kcal $ME·d^{-1}$.

Requirements and Allowances for Adult Dogs

The data of Hedhammar et al. (1980) and Gershoff (1958) showed that adult dogs can be maintained on diets containing concentrations of approximately 1.5 g $Ca·kg^{-1}$ diet, which provided approximately 20 mg Ca·kg $BW^{-1}·d^{-1}$. Endogenous fecal losses of approximately 20 mg Ca·kg $BW^{-1}·d^{-1}$would require almost 100 percent true bioavailability of Ca and an apparent Ca availability of close to 0 percent (Hedhammar et al., 1980; Hill et al., 2001). Schoenmakers et al. (1999) in Great Dane puppies and Nap et al. (1993) in miniature poodle puppies also found endogenous fecal losses averaging about 20 mg Ca·kg $BW^{-1}·d^{-1}$. Zero calcium balance would require minimal losses of Ca in the urine, which has been confirmed (Hedhammar et al., 1980; Schoenmakers et al., 1999).

These data suggest that to maintain Ca balance adult dogs must absorb approximately 25 mg of Ca·kg $BW^{-1}·d^{-1}$. Assuming a maximal true bioavailability of 90 percent, the MR of Ca for adult dogs would be no more than 30 mg·kg $BW^{-1}·d^{-1}$, which could be provided by a diet containing 0.5 g per 1,000 kcal ME or 2 g $Ca·kg^{-1}$ and 4,000 kcal $ME·kg^{-1}$.

Assuming a safety factor of 50 percent (bioavailability of 40 percent) to account for variations in fractional absorption and energy intake, the RA of dietary Ca for adult dogs could reasonably be set at 65 mg·kg $BW^{-1}·d^{-1}$ (130 mg·kg $BW^{-0.75}·d^{-1}$). The RA for a 15-kg adult dog consuming 1,000 kcal ME·d^{-1} would be met by a diet containing 1.0 g Ca per 1,000 kcal ME or 4.0 g Ca·kg^{-1}, DM basis, and 4,000 kcal ME·kg^{-1}.

Requirements and Allowances for Gestation and Lactation in Dogs

Using a factorial approach, Meyer (1984) reported RAs of Ca for pregnant bitches as 160 mg·kg $BW^{-1}·d^{-1}$ during the last 3 weeks of pregnancy assuming a bioavailability of 40 percent. This figure was confirmed in a subsequent study in pregnant bitches of several breeds (Meyer et al., 1985a). The energy requirement in late pregnancy for a 22-kg bitch would be approximately 100 kcal ME·kg $BW^{-1}·d^{-1}$ (Meyer et al., 1985a). A diet containing 1.6 g Ca per 1,000 kcal ME or 6.4 g Ca·kg^{-1} and 4,000 kcal ME·kg^{-1} should provide the RA of Ca for gestation.

During lactation, again using a factorial approach, Meyer et al. (1985b) calculated the Ca allowance of a 22-kg bitch nursing eight puppies to be 360 mg·kg $BW^{-1}·d^{-1}$ assuming 50 percent bioavailability. The energy requirement for a 22-kg bitch nursing eight pups during late lactation may be estimated at 230 kcal ME·kg $BW^{-1}·d^{-1}$, or approximately 5,000 kcal ME (Meyer et al., 1985b). Based on these data, a diet containing 1.6 g Ca per 1,000 kcal or 6.5 g Ca·kg^{-1} and 4,000 kcal ME·kg^{-1} should provide the recommended Ca allowance for a 22-kg lactating bitch with eight puppies in peak lactation. Since a slightly lower energy intake and a slightly higher Ca need were reported for giant breeds, the Ca concentration of a diet designed for giant breeds might have to be increased slightly to about 1.9 g Ca per 1,000 kcal ME (Meyer et al., 1985b).

The requirements for lactation can also be inferred by factorial analysis using data on milk production and milk Ca concentration. Lonnerdal et al. (1981) and Lonnerdal (1996) reported Ca concentrations in bitch milk averaging about 1,700 mg·L^{-1}. Ruesse (1961) and Oftedal (1984) reported peak milk production of approximately 1,050 and 1,700 mL·d^{-1} in beagle and German shepherd bitches, respectively, when they were nursing six puppies. By assuming a minimum Ca requirement for maintenance of 30 mg·kg $BW^{-1}·d^{-1}$ at a maximal bioavailability of 90 percent, the MR for milk production would be 150-200 mg·kg $BW^{-1}·d^{-1}$ for maintenance plus lactation. To correct for variations in availability, an average bioavailability of 65 percent might be assumed, which would result in a RA of 200-300 mg·kg $BW^{-1}·d^{-1}$ (433-650 mg·kg $BW^{-0.75}·d^{-1}$) for lactating bitches. This amount of Ca would be supplied by a diet containing 5.0 g Ca·kg^{-1}, DM basis (1.25 g per 1,000 kcal ME), if the diet contained 4,000 kcal ME·kg^{-1}, which is very similar to the data of Meyer (1984).

To ensure adequate Ca for lactating bitches of all breeds, the adequate intake (AI) and RA for Ca should be set at the level determined adequate for giant breeds, i.e., 380 mg Ca·kg $BW^{-1}·d^{-1}$ (820 mg Ca·kg $BW^{-0.75}·d^{-1}$), which, given normal energy intake, would require 1.9 g Ca per 1,000 kcal ME or 8 g Ca·kg^{-1} in a diet containing 4,000 kcal ME·kg^{-1} (Meyer et al., 1985b). As shown above, a diet providing sufficient Ca for lactation should be more than sufficient for gestation.

Safe Upper Limit of Calcium in Dogs

Data on adverse effects of excessive Ca consumption are available for growing puppies of giant breeds (Hedhammar et al., 1974; Hazewinkel et al., 1985, 1991; Goedegebuure and Hazewinkel, 1986; Voorhout and Hazewinkel, 1987). These studies showed that feeding diets with concentrations of 21-33 g Ca·kg^{-1}, DM basis (4.9-8.9 g Ca per 1,000 kcal ME), resulted in significant bone abnormalities in growing dogs of giant breeds. However, Weber et al. (2000) reported no abnormalities when diets containing 2.1-3.9 g Ca per 1,000 kcal ME were fed to Great Dane or giant schnauzer puppies for 24 weeks beginning at 10 weeks of age. In growing puppies of medium- to large-sized breeds, Laflamme (2000) found no adverse skeletal effect of feeding diets containing 3.9-5.7 g Ca per 1,000 kcal ME (13-19 g Ca·kg^{-1}) in a diet containing 3,300 kcal ME·kg^{-1}, DM basis. Based on these data, a safe upper limit (SUL) for Ca in growing giant-breed puppies may reasonably be set at a minimum of 4.5 g per 1,000 kcal ME or 18 g Ca·kg^{-1} in a diet containing 4,000 kcal ME·kg^{-1}, DM basis. For puppies of large breeds with slow growth rates, as well as those of smaller breeds and all adult dogs, the SUL will very likely be higher.

Absorption and Bioavailability of Dietary Calcium in Cats

Less information is available on Ca absorption in the feline compared to the canine species. Pastoor et al. (1994b) studied the effects of calcium chloride ($CaCl_2$) on mineral metabolism in kittens fed purified diets containing 6.7 g Ca·kg^{-1} diet as the carbonate or the chloride and 12.3 g Ca·kg^{-1} diet, with equal amounts from calcium carbonate ($CaCO_3$) and $CaCl_2$. Balance trials were performed at 15, 21, 31, and 39 weeks of age. Apparent absorption of Ca intake in 15-week-old kittens averaged 45 percent when the animals were fed diets containing 6.7 g Ca·kg^{-1} as either the carbonate or the chloride and 24 percent when fed diets containing 12.3 g Ca·kg^{-1} with equal amounts of Ca as carbonate and chloride. This decreased gradually to apparent absorptions of 5-10 percent for diets containing 6.7 g Ca·kg^{-1} as carbonate or chloride and less than 1 percent for the diet

containing 12.3 g Ca·kg^{-1} as carbonate or chloride in 39-week-old cats.

In adult ovariectomized cats approximately 1.5 years of age, Pastoor et al. (1994a) found apparent absorption of intake averaging 7.5, 18.4, 5.1, and 18.2 percent in diets containing 2.5, 3.7, 7.5, and 15.2 g Ca·kg^{-1}, DM basis, as calcium carbonate. In a similar experiment, apparent absorptions of 5 percent were observed when purified diets containing 7 g Ca·kg^{-1} were fed as either the $CaCO_3$ or $CaCl_2$ (Pastoor et al., 1994b). In another experiment, Pastoor et al. (1995a) found apparent absorption of intake averaging 12.5 percent in 2.5-year-old ovariectomized cats fed a purified diet containing 7 g Ca·kg^{-1} as $CaCO_3$. Also, 3-year-old cats fed diets containing 13 g Ca·kg^{-1} as $CaCO_3$, or equal amounts of $CaCO_3$ and $CaCl_2$ were observed to have apparent absorption values ranging from 0 to 9 percent.

Purified diets have been used in most studies of Ca absorption in cats (Pastoor et al., 1994b,1994a, 1995a). However, in a study of Ca absorption in adult cats fed basal diets with ground limestone, dicalcium phosphate, or bone meal as the source of Ca, Hintz and Schryver (1986) reported that from any of the three sources, positive Ca balance was attained at a dietary Ca concentration of 2 g Ca·kg^{-1}, DM basis, the diets having a Ca:P ratio of 1:3.5. True absorption of Ca in these studies was estimated at 36-39 percent.

The effect of various calcium salts on Ca absorption in cats has also been studied. Feeding Ca as the chloride compared to the carbonate resulted in a higher percentage of Ca absorption and a lower urinary pH (Pastoor et al., 1994b). In other studies, however, addition of 1.5 percent ammonium chloride to a standard diet was shown to result in a reduction in the apparent absorption of Ca intake from an average of about 12 percent to approximately 5 percent during the first several months of feeding. However, this effect disappeared during the fifth and sixth month of feeding the diet containing ammonium chloride (Ching et al., 1989). Recent studies in cats suggest that alterations in the Ca:P ratio (increases in dietary P) do not significantly affect Ca absorption in adult cats (Pastoor et al., 1995b).

Calcium Deficiency in Cats

Scott et al. (1961) described Ca deficiency in kittens fed a diet consisting mainly of raw beef heart, which contains approximately 30 mg Ca·kg^{-1} diet on a DM basis. Affected kittens demonstrated bone rarefaction, especially in the lumbar vertebrae, which tended to curve and collapse, and in the the pelvis (Pennington, 1998; Scott et al., 1961). Similar findings were observed in an experiment by Krook et al. (1963) which were compatible with a diagnosis of NSHP. There was a loss of bone mineral, evident with both radiographic and histologic evaluation. Affected animals showed evidence of bone pain, which proceeded to pathological fractures. Wing (1967) found in kittens that the clinical signs of Ca deficiency could be reversed by feeding a diet containing 10 g Ca·and 5 g P·kg^{-1} diet. Jowsey and Gershon-Cohen (1964) reported radiologic evidence of decreased mineral density in adult cats fed a raw beef heart diet for 10 weeks. Decreased bone density was more pronounced after 20 weeks in cats fed the raw beef heart diet, but animals supplemented with Ca after 10 weeks showed improvement.

Adverse Effects of Excess Consumption of Calcium in Cats

There is some evidence of deleterious effects of elevated dietary Ca on kittens. Howard et al. (1998) evaluated the Mg requirement of kittens fed a purified basal diet containing 6 or 23 g Ca·kg^{-1}, DM basis. Kittens fed the high- versus normal-Ca diet had depressed food intake, decreased growth, and higher serum concentrations of both total and ionized Ca. The high-Ca diet also increased the requirement for Mg (Howard et al., 1998). Pastoor et al. (1994b) observed decreased apparent Ca availability, 24 percent versus 40 percent, and increased bone mineral density, in 15-week-old kittens fed a purified diet containing 12.3 versus 6.7 g Ca·kg^{-1} diet, DM basis, respectively.

Dietary Calcium Requirements and Allowances in Cats

Requirements and Allowances for Kittens

There is likely less breed variation in the Ca requirements of cats compared to dogs. However, as in the dog, the Ca requirement of kittens appears to decrease with increasing age (Pastoor et al., 1994b). Scott (1965) suggested that kittens require between 200 and 400 mg Ca·d^{-1} assuming the Ca:P ratio is not too high or too low. Pastoor et al. (1994b) reported Ca intakes of 300 mg·kg BW^{-1}·d^{-1} and an apparent percentage absorption of about 40 percent in 15-week-old kittens fed a purified diet containing 6.7 g Ca·kg^{-1}, DM basis. This decreased to 120 mg Ca·kg BW^{-1}·d^{-1} and an apparent percentage absorption of about 10 percent at 39 weeks of age (Pastoor et al., 1994b). Howard et al. (1998) observed normal growth rates in 10- to 22-week-old kittens fed a purified diet with an average daily Ca intake of 200 mg·kg BW^{-1}·d^{-1}. Morris and Earle (1999) suggested that a dietary concentration of 6 g Ca·kg^{-1}, DM basis (approximately 1.3 g Ca per 1,000 kcal ME), would meet the Ca need of growing kittens as long as the Ca:P ratio is reasonable (approximately 1:0.6-1:1.3). An 800-g kitten consuming 180 kcal ME would thus have a minimum Ca requirement of 295 mg·kg BW^{-1}·d^{-1} (274 mg·kg BW$^{-0.67}$·d^{-1}) (Morris and Earle, 1999).

For a RA, accounting for reductions in Ca availability in standard diets, a true absorption of 50 percent can be assumed (Hashimoto et al., 1996) for growing kittens assuming an endogenous fecal Ca loss of 20 mg·kg BW^{-1}·d^{-1}

(Hashimoto et al., 1996; Kienzle, 1998). Assuming 75 percent true absorption of Ca in the purified diet fed by Morris and Earle (1999), similar to that estimated by Pastoor et al. (1994b), the recommended Ca allowance for the growing kittens may be set at 440 mg·kg $BW^{-1}·d^{-1}$ (410 mg·kg $BW^{-0.67}·d^{-1}$). A diet containing 2.0 g Ca per 1,000 kcal ME would provide the recommended Ca allowance for an 800-g kitten consuming 180 kcal ME·d^{-1}.

Requirements and Allowances for Adult Cats

Pastoor et al. (1994a) evaluated Ca balance in 1.5-year-old ovariectomized cats and found that those fed diets with a Ca concentration of 2.5 g Ca·kg^{-1} were in positive Ca balance, indicating that the diet was sufficient. In another study, Pastoor et al. (1994b) observed apparent Ca absorption of less than 10 percent in 2.5-year-old ovariectomized cats fed purified diets containing 7 g Ca·kg^{-1}, suggesting that Ca intake was greater than necessary. Kienzle (1998) used a factorial approach to calculate the Ca requirement of lactating queens, which included an estimate of a MR for maintenance of 21.2 mg·kg $BW^{-1}·d^{-1}$. With an estimated bioavailability of 35 percent, a maintenance allowance of 61 mg Ca·kg $BW^{-1}·d^{-1}$ was calculated.

Adult cats are usually in zero Ca balance with urinary Ca losses of about 1 mg·kg $BW^{-1}·d^{-1}$ and endogenous fecal losses of about 20 mg·kg $BW^{-1}·d^{-1}$ (Pastoor et al., 1994a; Kienzle, 1998). Assuming 90 percent maximal true availability, the MR of Ca for adult cats approximates 25 mg·kg $BW^{-1}·d^{-1}$ (40 mg·kg $BW^{-0.67}·d^{-1}$) (Pastoor et al., 1994a, 1995a; Kienzle, 1998). A diet containing 400 mg Ca per 1,000 kcal ME or 1.6 g Ca and 4,000 kcal ME·kg^{-1} would thus supply the minimum Ca requirement for a 4-kg adult cat consuming 250 kcal ME·d^{-1}.

Assuming an average true absorption of 45 percent, similar to that measured by Hintz and Schryber (1986) to account for variations in diet and other factors, the RA of dietary Ca for adult cats would be 45 mg·kg $BW^{-1}·d^{-1}$ (71 mg·kg $BW^{-0.67}·d^{-1}$). A diet containing 720 mg Ca per 1,000 kcal ME would provide the Ca allowance for a 4-kg cat consuming 250 kcal ME·d^{-1} (Pastoor et al., 1994a; Kienzle, 1998). This agrees well with the data of Hintz and Schryver (1986) who found that feeding basal diets containing 2-3 g Ca·kg^{-1} to adult cats resulted in slightly positive Ca balance even at a Ca:P ratio of 1:3.5.

Requirements and Allowances for Gestation and Lactation in Cats

There are no experimental data concerning the Ca requirement of queens during gestation. However, a diet containing sufficient Ca to support the growth of kittens (i.e., 2.0 g per 1,000 kcal ME) should provide an AI to support the Ca needs for maintenance plus gestation as long as energy intake is sufficient. This is virtually identical to the Ca concentration of a gestation-lactation diet successfully used by Piechota et al. (1995) to investigate the nitrogen requirements of cats during gestation and lactation.

There is also a paucity of experimental data on the Ca needs of lactating queens. Using a factorial approach, Kienzle (1998) calculated a Ca requirement of queens at peak lactation nursing four kittens of 358 mg·kg $BW^{-1}·d^{-1}$ (565 mg·kg $BW^{-0.67}·d^{-1}$) assuming Ca bioavailability of 35 percent. A 4-kg queen nursing four kittens in peak lactation would thus require a total of 1.43 g Ca·d^{-1}. A diet containing 2.7 g per 1,000 kcal ME would provide the RA of Ca for this purpose. This fits well with the data of Piechota et al. (1995) if one assumes that true absorption of the Ca intake in the purified diet used by this group was 90 percent or higher.

Safe Upper Limit of Calcium in Cats

Howard et al. (1998) reported reduced food intake and decreased growth rate in kittens fed diets containing an estimated 4.6 g Ca per 1,000 kcal ME. Pastoor et al. (1994b) suggested that feeding diets containing 2.6 g Ca per 1,000 kcal ME to kittens resulted in increased bone density when compared to diets with half the concentration of Ca. Based on these data, a SUL may be set somewhere between 2.6 and 4.6 g Ca per 1,000 kcal ME; thus the SUL cannot be defined precisely.

Phosphorus

Phosphorus is the sixth most prevalent chemical element and the second (after Ca) most prevalent mineral element in mammals, including humans (Lobaugh, 1996), dogs, and cats (Kienzle et al., 1991b, 1998b). As with Ca, the highest proportion of P, about 86 percent, is present in bone. Phosphorus is also found in some abundance in other tissues, the most prominent of these being muscle, which accounts for some 8.6 percent of total body P. The P concentration in newborn puppies is about 4.7 g·kg BW^{-1}, which increases to 5.9 g·kg^{-1} in the adult (Kienzle et al., 1998b). In cats, the concentrations in newborn and adult animals are 3.8 and 9.1 g·kg BW^{-1}, respectively (Kienzle et al., 1991b). Like Ca, P serves a major role as a structural element of the skeleton. It is also a structural component of DNA and RNA, and of membranous and other phospholipids and phosphoproteins. As a component of high-energy phosphate compounds, it serves a vital function in energy metabolism including locomotion. It also plays a role in acid-base balance (Lobaugh, 1996).

In feedstuffs, P is more ubiquitous than Ca. For example, it is present at relatively high concentrations in both cereal and dairy products (NRC, 1971; Pennington, 1998). However, in cereal and other vegetable products a significant fraction of P may be present in the form of phytate (salts of hexaphosphorylated inositol), which is less bioavailable

than other forms of P (Hoff-Jorgensen, 1945; Erdman, 1979; Graf, 1986). Fresh meat products generally contain around 0.3 percent P on a DM basis and have a Ca:P ratio of about 1:20 (Pennington, 1998). However, parts of animal carcasses containing bone have much higher concentrations of both P and Ca (NRC, 1971). Commonly used P sources in dog and cat foods, in addition to meat, include meat and bone meal, 4.46 percent P; fish meal, 3.05 percent P; bone meal, 12.86 percent P; dibasic calcium phosphate, 19.30 percent P; dibasic ammonium phosphate, 20.6 percent P; and phosphoric acid, 31.6 percent P (Tables 13-6 and 13-8).

Absorption and Bioavailability of Dietary Phosphorus in Dogs

There are few data on the absorption of dietary P in dogs. Jenkins and Phillips (1960a) reported apparent absorption of P intake of 30-76 percent in German shepherd puppies 6 to 16 weeks of age fed diets containing 1.7-5.3 g $P \cdot kg^{-1}$, mainly in the form of disodium phosphate. In subsequent studies in German shepherd, cocker spaniel, and beagle puppies, apparent absorption of P intake from a standard diet containing 3.3 g $P \cdot kg^{-1}$ was 66 percent when the Ca concentration was 6 g $Ca \cdot kg^{-1}$ diet (Ca:P ratio 1.8:1). When the Ca concentration was raised to 9 and 12 g $Ca \cdot kg^{-1}$ diet (Ca:P ratios of 3-4:1), apparent absorption of P intake declined to 57 percent and 49 percent, respectively. Apparent absorption of phytate-derived dietary P was inversely related to increasing Ca:P ratio (Jenkins and Phillips, 1960b). Increasing dietary fat from 3 to 20 percent did not alter P absorption in diets containing 3.3 or 4.1 g $P \cdot kg^{-1}$. In a study of P metabolism in growing Great Dane puppies, Schoenmakers et al. (1999) fed diets containing 8.2 g $P \cdot kg^{-1}$ and 10.4 or 31.1 g $Ca \cdot kg^{-1}$, DM basis. Apparent absorptions of P of 65-70 percent and 25-50 percent were observed in 9- and 15-week-old puppies, respectively, for the two diets, with high dietary Ca significantly reducing absorption of P (Schoenmakers et al., 1999). However, all puppies were in positive P balance.

Sheffy et al. (1985) observed apparent absorption of P averaging 40 percent in adult dogs 1 or 10 years of age when they were fed standard diets containing 9.9-20.7 g $P \cdot kg^{-1}$ diet and 12.3-36.0 g $Ca \cdot kg^{-1}$.

With respect to dietary interactions, there is ample evidence that increasing the dietary concentration of Ca decreases the absorption of P (Jenkins and Phillips, 1960b; Schoenmakers et al., 1999). This is most evident at Ca:P ratios greater than 2:1. There is also good evidence, in dogs as well as other simple-stomached animals, that phytate P is less bioavailable than P from inorganic sources (Jenkins and Phillips, 1960a,b). For example, apparent absorption of P has ranged from 26 percent in diets containing all beef as protein source to as low as 13.5 percent in diets containing a mixture of beef and soy protein, which is relatively high in phytate content (Hill et al., 2001).

Phosphorus Deficiency in Dogs

Deficiencies of P have been reported in puppies (Table 7-1). Puppies fed diets containing 3.3 g $P \cdot kg^{-1}$ (67 percent apparent digestibility) and 6 g $Ca \cdot kg^{-1}$ (Ca:P ratio 1.8:1) demonstrated better growth than those fed lower concentrations of P (Jenkins and Phillips, 1960b). Puppies fed diets with similar concentrations of P but higher concentrations of Ca had reduced P absorption as evidence by reduced plasma P and bone ash concentrations (Jenkins and Phillips, 1960b).

Adverse Effects of Excess Consumption of Phosphorus in Dogs

There are very few data regarding the effects of elevated dietary P intake in dogs. The effects of very low Ca:P ratios (i.e., nutritional secondary hyperparathyroidism) have been well described (Henrikson, 1968; Krook et al., 1971). However, this appears to be related more to Ca deficiency than it does to P excess (Hazewinkel et al., 1991).

Dietary Phosphorus Requirements and Allowances for Dogs

Requirements and Allowances for Puppies

The above data suggest that the apparent absorption of P intake in young dogs fed inorganic sources of this mineral is at least 70 percent (Jenkins and Phillips, 1960a,b). If dogs are similar to cats, endogenous fecal losses of P would be only a few milligrams per kilogram of body weight (BW) per day (Kienzle, 1998). However, if the Ca:P ratio exceeds 2:1 or the diet contains significant amounts of phytate P, absorption will decrease (Jenkins and Phillips, 1960a,b; Schoenmakers et al., 1999). A usable figure for percentage absorption of P intake in young dogs fed standard growth diets, particularly dry diets, may reasonably be set at about 50 percent (Jenkins and Phillips, 1960a). For young dogs, a

TABLE 7-1 Clinical Signs of Phosphorus Deficiency in Dogs in Relation to Physiological Status and Dietary Phosphorus Concentration

Physiological Status	Dietary P ($g \cdot kg^{-1}$ DM)	Clinical Signs	Reference
German shepherd puppies	2.3	Reduction and cessation of weight gain, poor appetite, emaciation, and bowing and swelling of the forelimbs and carpi	Jenkins and Phillips (1960a)
Puppies	3.3	Reduced growth	Jenkins and Phillips (1960b)

minimum absorbable P concentration has been estimated to be about 2.6 g P·kg^{-1} diet, DM basis (Jenkins and Phillips, 1960a). Therefore, a reasonable dietary P concentration for growth of puppies could be about 5.2 g P·kg^{-1}, DM basis.

Schoenmakers et al. (1999) observed an apparent absorption of P intake of 70 percent when 10- to 15-week-old Great Dane puppies were fed a diet containing 0.82 percent P, or 2.2 g P·1,000 kcal ME^{-1} (Ca:P ratio of 1.3:1), with a net P retention of approximately 190 mg·kg BW^{-1}·d^{-1}. However when the Ca:P ratio was increased to 3.6:1, net P retention decreased to 95 mg·kg BW^{-1}·d^{-1} and urinary P loss was negligible, suggesting that this may be an insufficient amount of P (Schoenmakers et al., 1999).

Based on these data, to ensure adequate P especially in the face of increased dietary Ca the AI of P should be set at 2.50 g per 1,000 kcal ME. This diet will provide 450 mg·kg BW^{-1}·d^{-1} (680 mg·kg BW$^{-0.75}$·d^{-1}) of P, or a 5.5-kg puppy consuming 1,000 kcal ME·d^{-1}, which should meet the need of a giant-breed puppy while perhaps exceeding that of growing puppies of small- or medium-sized breeds (Jenkins and Phillips, 1960a,b).

Requirements and Allowances for Adult Dogs

There are very few experimental data available from which to recommend a MR or RA of P in adult dogs. Sheffy et al. (1985) reported apparent absorptions of ingested P of 40-50 percent in young adult and old beagles fed diets containing 10.0-25.0 g P·kg^{-1}, DM basis. If energy consumption is normal, the P intake of these dogs would be approximately 220 mg·kg BW^{-1}·d^{-1}. With a true absorption of only 40 percent, the absorbed P, 90 mg·kg BW^{-1}·d^{-1}, would be much higher than is reasonable based on observed Ca requirements of adult dogs (Gershoff et al., 1958; Hedhammar et al., 1980).

More recently, Hill et al. (2001) measured apparent absorption of ingested P in adult dogs fed diets containing various amounts of animal and plant protein sources. The dietary P concentration averaged 10.5 g·kg^{-1}, DM basis, and the Ca:P ratio was 2:1. Phosphorus intake was estimated at 132 mg·kg BW^{-1}·d^{-1}, and apparent absorption of P intake averaged 22 percent, resulting in a net P uptake of 30 mg·kg BW^{-1}·d^{-1}. One may presume that the endogenous fecal loss of P was only a few milligrams per kilogram of BW per day based on the data of Kienzle (1998) in cats, so true absorption was probably no higher than 35 mg·kg BW^{-1}·d^{-1}. This figure is very close to the maintenance P allowance predicted by Meyer (1984) in pregnant bitches and suggests a true absorption of close to 30 percent. Diets with a lower Ca:P ratio (closer to 1:1) could be expected to result in a higher percentage P absorption, perhaps closer to the 70 percent reported by Jenkins and Phillips (1960a,b), suggesting an AI for adult dogs of 50 mg·kg BW^{-1}·d^{-1} (100 mg·kg BW$^{-0.75}$·d^{-1}). A diet containing approximately 0.75 g P per 1,000 kcal would provide sufficient P for a 15-kg adult dog consuming 1,000 kcal ME·d^{-1}.

Requirements and Allowances for Gestation and Lactation in Dogs

There are few data available on P requirements for gestation and lactation in the bitch. Meyer et al. (1985a) recommended a P allowance for pregnant bitches during the last 5 weeks of pregnancy of 133 mg·kg BW^{-1}·d^{-1}. For lactating bitches, Meyer et al. (1985b) recommended a daily P allowance of 145-290 mg·kg BW^{-1}·d^{-1}. These estimates were based on the size of the bitch and an assumed P bioavailability of 50 percent. Extrapolating from these data, an estimated 270 mg P·kg BW^{-1}·d^{-1} (580 mg·kg BW$^{-0.75}$·d^{-1}) would be the AI and the RA for a 22-kg bitch in peak lactation nursing eight puppies. If an energy intake of 5,000 kcal ME·d^{-1} is assumed, a diet containing 1.2 g P per 1,000 kcal ME would provide the RA and could be used for both gestation and lactation.

Safe Upper Limit of Phosphorus for Dogs

There are insufficient data on which to base an SUL for P in dogs.

Absorption and Bioavailability of Dietary Phosphorus in Cats

More information is available regarding phosphorus availability in cats as compared to that in dogs, but there are only a few studies in kittens. Pastoor et al. (1994b) fed growing kittens, 15 to 39 weeks of age, purified diets containing 5.1 g phosphorus·kg^{-1} diet as monobasic ammonium phosphate and either 6.7 or 12.5 g calcium·kg^{-1} (Ca:P ratios of 1.3:1 or 2.5:1). Apparent absorption of intake P averaged 85-70 percent for the diet with the lower concentration of Ca and 60-40 percent when the higher Ca diet was fed, the higher dietary Ca:P ratio resulting in about a 30 percent reduction in apparent absorption of intake P (Pastoor et al., 1994b). Later, Pastoor et al. (1995c) evaluated P metabolism in kittens aged 11 to 39 weeks fed purified diets containing 5.4 or 2.8 g P·kg^{-1} as monobasic ammonium phosphate and 7.1 g Ca·kg^{-1} diet as the carbonate (Ca:P ratios of 1.3:1 and 2.5:1) on a DM basis. Apparent absorption of intake P was close to 90 percent in 11- or 15-week-old kittens fed either diet, gradually decreasing to 65-70 percent at 39 weeks of age. Kittens fed 2.8 g P·kg^{-1} diet showed significant reductions in BW compared to kittens fed 5.4 g P·kg^{-1} diet between 15 and 20 weeks of age, but at 39 weeks there were no significant differences between the two groups (Pastoor et al., 1995c). Similar results were observed in 31-week-old kittens fed a diet containing 2.8 g P·kg^{-1} and 3.8 g Ca·kg^{-1} (Ca:P ratio of 1.4:1).

Adult cats (2.5 years of age) fed purified diets containing 5.1 g P·kg^{-1} (Ca:P ratio 1.4:1) and increasing concentrations of Mg (0.2-1.6 g·kg^{-1} diet) demonstrated decreasing apparent percentage absorption of P from 73 percent to 63 percent. A concentration of 0.8 or 1.6 g Mg·kg^{-1} diet had a small but significant negative effect on apparent P absorption compared to a diet containing 20 mg Mg·kg^{-1} (Pastoor et al., 1995a). One-year-old cats fed purified diets containing 2.8, 5.6, 11.2, and 16.9 g P and 6.7 g Ca·kg^{-1} diet (Ca:P ratio 2.4-0.4:1) demonstrated increasing apparent percentage absorption of P ranging from 67 to 77 percent as the P concentration of the diet increased and the Ca:P ratio decreased (Pastoor et al., 1995b).

Kienzle (1998) investigated P requirement in adult cats 1.5-6 years of age. Diets containing 2.1, 3.8, or 4.1 g P·kg^{-1} were fed (Ca:P ratios varying from 1:1 to 4:1). Feeding diets with a Ca:P ratio of 1:1 resulted in apparent P absorption averaging 50 percent when the P concentration was either 2.1 or 4.1 g·kg^{-1}. Ca:P ratios of 2:1 significantly reduced apparent P absorption regardless of dietary concentration, and ratios of 4:1 resulted in even more drastic reductions in P absorption, with cats fed a diet containing 8 g Ca·kg^{-1} and 2 g P·kg^{-1} demonstrating negligible P bioavailability. These cats developed clinical signs of P deficiency (Kienzle et al., 1998a). The Ca:P ratio had a greater impact than dietary P concentration on apparent percentage absorption of P in this study.

Organically bound P from animal sources, when compared to inorganic P, has also been found to reduce apparent absorption of P from 40 percent to 20 percent in adult cats fed a standard diet containing an estimated 16 g P·kg^{-1}, DM basis (Finco et al., 1989).

Phosphorus Deficiency in Cats

There is only one report of P deficiency in cats. Kienzle et al. (1998a) described clinical signs of deficiency including hemolytic anemia, locomotor disturbances, and metabolic acidosis in adult cats fed diets containing 2.1 g P·kg^{-1} and 8.3 g Ca·kg^{-1}, DM basis (Ca:P ratio of 4:1). In this study, P intake averaged approximately 20 mg·kg BW^{-1}·d^{-1}, with an apparent absorption of dietary P averaging about 20 percent (Kienzle et al., 1998a).

Adverse Effects of Excess Consumption of Phosphorus in Cats

While Pastoor et al. (1995b) and Morris and Earle (1999) observed an inverse relationship of dietary to plasma P concentrations (no adverse clinical signs were noted) as dietary P intake increased from 30 to 160 mg·kg BW^{-1}·d^{-1}, this has since been reported to be an artifact of experimental procedure (J. G. Morris, personal communication, 2002). Fulton and Fruechte (1991) observed clinical signs of depression, dehydration, metabolic acidosis, and hyperphosphatemia with excessive supplemental P, but this study included only one observation.

Dietary Phosphorus Requirements and Allowances for Cats

Requirements and Allowances for Kittens and Adult Cats

Scott (1965) stated that kittens fed purified diets require 150-200 mg P·d^{-1}, but kittens fed standard diets usually consume up to 400 mg P·d^{-1}, requiring Ca supplementation to attain a reasonable Ca:P ratio. Pastoor et al. (1995c) measured P balance in 11- to 39-week-old kittens fed a purified diet containing 2.8 or 5.6 g P·kg^{-1} and 7.1 g Ca·kg^{-1}, DM basis. Although kittens fed the diet with the lower P concentration initially grew more slowly, at 39 weeks there were no significant differences between the two groups (Pastoor et al., 1995c). From studies of P requirements of kittens, Pastoor et al., (1995c) concluded that feeding diets containing 1.2 g P per 1,000 kcal ME with a Ca:P ratio of 2:1 resulted in normal P balance. Such a diet would provide an intake of 270 mg P·kg BW^{-1}·d^{-1} (251 mg·kg BW$^{-0.67}$·d^{-1}) for an 800-g kitten consuming 180 kcal ME·d^{-1}, which may be considered a MR.

Pastoor et al. (1995b) evaluated P balance in 1-year-old ovariectomized cats fed purified diets containing 2.8-16.9 g P·kg^{-1}, DM basis, with a constant Ca concentration of 6.7 g·kg^{-1} diet (Ca:P ratios of 2:1-1:2). Phosphorus balance was maintained at the lowest concentration of dietary P (Pastoor et al., 1995b). Also in adult cats, Kienzle et al. (1998a) determined that a dietary concentration of 2.1 g P·kg^{-1}, DM basis, appeared to maintain P balance if the Ca:P ratio was 2:1 or less. In adult cats, diets containing 0.35 g P per 1,000 kcal ME should maintain P balance (Kienzle et al., 1998a). The MR for a 4-kg adult cat consuming 250 kcal ME·d^{-1} would thus be 22 mg·kg BW^{-1}·d^{-1} (35 mg·kg BW$^{-0.67}$·d^{-1}).

While the Ca:P ratio is unlikely to be so high as to interfere with P availability, in most cat foods, particularly dry type, a portion of P probably will be present in the form of phytate, which is less available than that from inorganic sources. Therefore, it is prudent to account for differences in percentage absorption of dietary P and variations in energy intake. With MRs of 270 and 22 mg·kg BW^{-1}·d^{-1} (251 and 35 mg·kg BW$^{-0.67}$·d^{-1}) for young kittens and adult cats, respectively, RAs of 400 mg·kg BW^{-1}·d^{-1} (372 mg·kg BW$^{-0.67}$·d^{-1}) for kittens and 40 mg·kg BW^{-1}·d^{-1} (63 mg·kg BW$^{-0.67}$·d^{-1}) for adult cats are suggested. A diet containing 1.8 g P per 1,000 kcal ME would provide the recommended daily P allowance for an 800-g kitten consuming 180 kcal ME·d^{-1}. A diet containing 640 mg P per 1,000 kcal ME would provide the RA for a 4-kg adult cat consuming 250 kcal ME·d^{-1}.

Requirements and Allowances for Gestation and Lactation in Cats

Piechota et al. (1995) fed a purified diet containing 1.22 g P per 1,000 kcal ME to queens throughout gestation and lactation and reported no evidence of P deficiency. By use of factorial analysis, however, Kienzle (1998) estimated P requirements in lactating queens to be 100-303 mg·kg $BW^{-1}·d^{-1}$ depending on the number of kittens (two to six) in the litter and assuming a P bioavailability of 35 percent. Based on the data of Piechota et al. (1995), a dietary P concentration of 4.9 g $P·kg^{-1}$ DM and 4,000 kcal $ME·kg^{-1}$ providing 165 mg·kg $BW^{-1}·d^{-1}$ (261mg·kg $BW^{-0.67}·d^{-1}$) for a 4-kg lactating queen nursing four kittens may be assumed to be the minimum P requirement for this life stage. Using the data of Kienzle et al. (1998) a recommended P allowance of 263 mg·kg $BW^{-1}·d^{-1}$ (411 mg·kg $BW^{-0.67}·d^{-1}$) can be made. A diet containing 1.9 g P per 1,000 kcal ME would thus provide the RA for a 4-kg queen nursing four kittens and consuming 540 kcal $ME·d^{-1}$.

Safe Upper Limit of Phosphorus for Cats

There is little information on which to base a SUL for dietary P intake in cats. Pastoor et al. (1995b) fed adult cats a semipurified diet containing 3.6 g P per 1,000 kcal ME (Ca:P ratio 0.4:1.0) for 4 weeks with minimal significant effects. However, cats fed this level of P did demonstrate a small decrease in renal creatinine clearance and decreased plasma P concentrations, perhaps an artifact, compared to cats fed diets with concentrations of 2.3 g P per 1,000 kcal ME or lower. Based on these data, the SUL for dietary P concentration for adult cats might be set at between 10 and 14 g $P·kg^{-1}$ in a diet containing 4,000 kcal $ME·kg^{-1}$. This estimate assumes a reasonably normal Ca:P ratio (0.5-1.5:1) and a reasonably high true absorption. If the Ca:P ratio is significantly higher than this estimate or absorption is low due to other factors, higher P intakes may be safe. Because of the effect of dietary Ca concentration and other dietary factors on P absorption, it is impossible to predict a SUL for dietary P in cats.

Magnesium

Magnesium is the second most abundant intracellular cation, after K, and is involved in more than 300 metabolic processes. Total body Mg in newborn kittens and adult cats has been measured as 200 mg and 400 mg·kg BW^{-1}, respectively, and in newborn puppies as approximately 100 $mg·kg^{-1}$ (Meyer et al., 1985a; Kienzle et al., 1991b). As a cofactor in enzyme function, it is essential for oxidative phosphorylation and adenosine triphosphatase (ATPase) activity, DNA and RNA metabolism, and protein synthesis. It also plays vital roles in the stability of muscle and nerve cell membranes, cell-to-cell adhesion, extracellular matrix communication, calcium channel regulation in cardiac tissue, lymphocyte proliferation, and platelet activation (Birk et al., 1998; de Chateau et al., 2001; McKee et al., 2002). It is required for the secretion and function of hormones (e.g., PTH) and plays an essential role in the mineral structure of bones and teeth (Levi et al., 1974; Khanna et al., 1998). About 50 percent of total body Mg is found in bone. Unlike Ca, however, bone Mg is not exchangeable. All but a small fraction of the remainder is found in the cytoplasm of soft tissues (e.g., muscle), with only about 1 percent in the extracellular fluid space (Favus, 1996).

Many ingredients used in petfoods provide sources of Mg. Muscle meat generally contains on the order of 0.1 percent Mg on a DM basis. However, meat and bone meals may contain more than 1.9 percent Mg. Various corn products contain from 0.1 to 0.6 percent Mg and soybean meal contains about 0.3 percent (NRC, 1971). Several inorganic sources of Mg are used as supplements in petfoods including ground limestone, 2.96 percent Mg; magnesium chloride, 12 percent Mg; magnesium sulfate, 9.8 percent Mg; and magnesium oxide, 9.8 percent Mg (Table 13-8).

Absorption and Bioavailability of Dietary Magnesium in Dogs

There are few data on the absorption of dietary Mg in dogs. Beynen et al. (2001) observed an apparent absorption of dietary Mg, in adult dogs fed a commercial moist diet, of 23 percent which increased to 30-36 percent with added lactulose. In another study, Beynen et al. (2002) reported that the addition of 10 $g·kg^{-1}$ of oligofructose to a basal dry diet increased the apparent absorption of Mg from 14 percent to 23 percent and suggested that this might be due to a decreased pH of the ileal ingesta resulting in increased solubility and absorption of Mg. Increasing dietary P concentration from 4.0 to 9.0 $g·kg^{-1}$ in a low-Mg (80 $mg·kg^{-1}$) diet accelerated the appearance of clinical signs of Mg deficiency, suggesting a negative effect of P on Mg bioavailability (Bunce et al, 1962a), whereas increasing dietary fat had no significant effect on bioavailability (Bunce et al., 1962b). Both BW and serum Mg concentrations were depressed in 1.5- to 7-year-old dogs fed diets containing 80 mg $Mg·kg^{-1}$ compared to 180 mg $Mg·kg^{-1}$, DM basis (Bunce et al., 1962b).

Magnesium Deficiency in Dogs

Vitale et al. (1961) induced Mg deficiency in weaned mongrel puppies by feeding a purified dry diet with no added Mg, the puppies developing hyperextension of the carpal joints and hind-leg paralysis. Two pups were then changed to a diet containing 240 mg $Mg·kg^{-1}$, DM basis, and promptly recovered, suggesting that an estimated 240 mg $Mg·kg^{-1}$ diet, DM basis, is sufficient for growth of puppies (Vitale et al., 1961).

In a series of two experiments, weanling mongrel or beagle puppies fed purified dry diets containing less than 140

mg Mg·kg^{-1} developed anorexia, weight loss, hyperextension of carpal joints, and posterior ataxia within 3 to 6 weeks of being fed the diets (Bunce et al., 1962a). Postmortem evaluation revealed mineralization of the thoracic aorta in the groups with clinical evidence of Mg deficiency (Bunce et al., 1962a). In a subsequent study, increasing dietary P concentration from 4 to 9 g P·kg^{-1} exacerbated the effects of low dietary Mg, while increasing dietary fat from 8 to 20 percent had no effect (Bunce et al., 1962b). Alterations in dietary Ca also did not appear to affect bioavailability of Mg. When 8-month-old dogs were fed diets containing 80 or 180 mg Mg·kg^{-1}, DM basis, serum Mg concentrations were reduced in those fed 80 mg Mg·kg^{-1} and some developed clinical signs of deficiency. In 1.5- to 7-year-old dogs, both BW and serum Mg concentration were depressed when the dogs were fed diets containing 80 mg compared to 180 mg Mg·kg^{-1}.

More recently, Cronin et al. (1982) produced clinical and serum chemical signs of Mg deficiency in adult beagle dogs by feeding a purified dry diet containing 170 mg Mg·kg^{-1}, DM basis. Stahlman et al. (2000) produced clinical signs of Mg deficiency, including lameness and hyperextension of the carpi, in beagle puppies after 4 weeks of feeding a diet containing 136 mg Mg·kg^{-1}, DM basis. Pedersen and Mow (1998) found a high incidence of hypomagnesmia in Cavalier King Charles spaniels that did not appear to be altered by Mg supplementation. They suggested that an increased probability of mitral valve prolapse might be related to the high incidence of hypomagnesemia in this breed.

Nonetheless, short-term (6 months) feeding of diets with a concentration of 200 mg Mg·kg^{-1}, DM basis, which is close to the MR, has been found to be effective, in conjunction with other dietary alterations, for the dissolution of Mg-containing uroliths in adult dogs (Osborne et al., 1985).

Adverse Effects of Excess Consumption of Magnesium in Dogs

There are no reported adverse effects of excess consumption of Mg in dogs. However, some natural water sources containing high concentrations of Mg salts might pose a risk for dogs.

Dietary Magnesium Requirements and Allowances for Dogs

Requirements and Allowances for Puppies and Adult Dogs

Kienzle et al. (1985) showed that normal nursing puppies consumed 13.4 mg mg·kg BW^{-1}·d^{-1} and 185 kcal ME·kg BW^{-1}·d^{-1} during the fourth week of lactation. If energy and Mg requirements are similar after weaning, a diet containing 75.0 mg Mg per 1,000 kcal would meet the requirement for a 5.5-kg puppy consuming 1,000 kcal ME·d^{-1}. However, it is likely that requirements after weaning are slightly lower and that the availability of Mg from standard diets is lower than that from milk. Further, long-term feeding of milk diets has been associated with hypomagnesemia in other species.

Data suggest that dietary Mg concentrations of 45 mg per 1,000 kcal ME provide MRs of Mg for both puppies and adult dogs fed purified dry diets (Bunce et al., 1962a,b; Cronin et al., 1982; Stahlmann et al., 2000). Such a diet would provide a Mg intake of 8.2 mg·kg BW^{-1}·d^{-1} (12.5 mg·kg BW$^{-0.75}$·d^{-1}) for a 5.5-kg puppy and 3.0 mg·kg BW^{-1}·d^{-1} (5.91 mg·kg BW$^{-0.75}$·d^{-1}) for a 15-kg adult dog, each consuming 1,000 kcal ME·d^{-1}.

A safe estimation may be that the bioavailability of Mg in standard diets is about half that of purified diets. Based on these data, to ensure adequate Mg content of standard diets, a concentration of 100 mg Mg per 1,000 kcal ME would be the RA for puppies. This would provide 18 mg Mg·kg BW^{-1}·d^{-1} (27.4 mg·kg BW$^{-0.75}$·d^{-1}) for a growing puppy, a figure that agrees well with the data of Kienzle et al. (1985).

The data of Beynen et al. (2002) indicate that Mg intake of adult dogs fed a commercial moist diet, containing an estimated 1.0 g Mg·kg^{-1}, DM basis, was 17.2 mg·kg BW^{-1}·d^{-1} and measured apparent absorption of Mg was 14.0 percent, providing apparent absorption of 2.0 mg·kg BW^{-1}·d^{-1}. Hill et al. (2001) evaluated Mg absorption in adult dogs fed diets containing 900 mg Mg·kg^{-1}, DM basis. The dogs in this study consumed 11.5 mg mg·kg BW^{-1}·d^{-1} with an apparent absorption of Mg intake of 7.5 percent, yielding an apparent absorption of approximately 1 mg mg·kg BW^{-1}·d^{-1} (Hill et al., 2001).

The above data suggest that the true requirement of Mg for adult dogs is somewhat more than the 2.0 mg·kg BW^{-1}·d^{-1} apparent absorption observed by Beynen et al. (2002) or 1.0 mg·kg BW^{-1}·d^{-1} observed by Hill et al. (2001), likely very close to the endogenous losses of Mg in adult dogs of 3 mg·kg BW^{-1}·d^{-1} reported by Meyer (1984) assuming zero Mg balance in adults. Using this value as the true requirement and a bioavailability of 30 percent as suggested by Meyer et al. (1985b), an intake of 10 mg Mg·kg BW^{-1}·d^{-1} (19.7 mg·kg BW$^{-0.75}$·d^{-1}) would constitute the RA of Mg for an adult dog. A diet containing 150 mg Mg per 1,000 kcal ME would provide this amount of Mg for a 15-kg adult dog consuming 1,000 kcal ME·d^{-1}.

Requirements and Allowances for Gestation and Lactation in Dogs

Summarizing several previous studies, Meyer (1984) listed recommended daily allowances of 15 and 23 mg Mg·kg BW^{-1}·d^{-1} for bitches during gestation and lactation, respectively. Subsequently, again using a factorial approach, Meyer et al. (1985b) revised the recommendation for Mg intake during lactation to as high as 32 mg·kg BW^{-1}·d^{-1} (69 mg·kg BW^{-075}·d^{-1}) in bitches of medium-size breeds with large litters. This recommendation assumed a 30 percent bioavailability of Mg. To meet the recommended daily allowance for Mg, a 22-kg bitch in peak lactation nursing

eight puppies would require a diet containing 150 mg Mg per 1,000 kcal ME. Such a diet would undoubtedly meet the needs for gestation as well (Meyer et al., 1985a).

Safe Upper Limit of Magnesium for Dogs

There is virtually no information on dietary Mg toxicity in dogs. Commercial dog foods frequently contain Mg concentrations of 0.8-1.7 g·kg^{-1} diet, DM basis. In the absence of specific information on dietary concentrations or intakes above which abnormalities are noted, it is impossible to provide a recommendation for the SUL of dietary Mg in dogs, other than to predict that it is >1.7 g Mg·kg^{-1} diet on a DM basis.

Absorption and Bioavailability of Dietary Magnesium in Cats

There is somewhat more information on Mg availability in cats than in dogs. Pastoor et al. (1994b) reported apparent absorption of Mg intake ranging from 56 percent to 15 percent in kittens from 15 to 39 weeks of age fed diets containing 360 mg·kg^{-1} and two dietary Ca concentrations of 6.7 and 12.5 g·kg^{-1}, respectively. Apparent absorption of Mg intake decreased with increasing age, and there was a tendency toward decreased absorption with higher concentration of Ca. In another study, Pastoor et al. (1995c) reported apparent absorptions of Mg from 81 percent to 12 percent in kittens fed diets containing 340 mg Mg·kg^{-1}, DM basis, as they aged from 11 to 39 weeks, in diets containing 7.1 g Ca·kg^{-1} and either 5.4 or 2.8 g P·kg^{-1}, DM basis.

In adult cats, apparent percentage absorption of Mg (340 mg·kg^{-1}of diet) decreased from 46.15 percent to 19.18 percent as the concentration of P was increased from 2.8 to 16.9 g P·kg^{-1} diet (Pastoor et al., 1995b). Decreased apparent absorption of Mg was positively correlated with urinary Mg excretion; no signs of Mg deficiency were reported.

Apparent percentage absorption of Mg (340 mg·kg^{-1} of diet) decreased from 40 percent to 26 percent as Ca concentration increased from 2.5 to 15.0 g·kg^{-1} (Pastoor et al., 1994a). Apparent Mg absorption and urinary Mg excretion were inversely correlated with dietary Ca concentration. In another study, Pastoor et al. (1994b) again observed a decrease in apparent absorption of Mg as Ca concentration of the diet increased. Further research by Howard et al. (1998) indicated a negative effect of increasing dietary Ca on the bioavailability of Mg. Pastoor et al. (1995a) observed a decrease in apparent absorption of Mg with increasing dietary Mg concentration.

Based on the above, the apparent absorption of Mg intake is negatively affected by increasing dietary concentrations of Ca, P, or Mg (Howard et al., 1998; Pastoor et al., 1994a,b, 1995a,b). Further, there is a negative correlation between age and apparent Mg absorption in growing kittens (Pastoor et al., 1994b, 1995c).

Magnesium Deficiency in Cats

Chausow et al. (1986) produced signs of Mg deficiency, including poor growth rate and overextension of the metacarpi followed by muscular twitching and convulsions, within 3 weeks of feeding growing kittens a diet containing approximately 42 mg Mg·kg^{-1}, DM basis. On postmortem evaluation, high Ca concentrations were found in the aorta compared to kittens fed diets containing 750 mg Mg·kg^{-1}. When kittens were fed diets containing 85 mg Mg·kg^{-1}, no clinical signs were observed, and growth rate was normal, but serum Mg concentrations were consistently lower than those observed in kittens fed diets containing 370 mg·kg^{-1}, DM basis.

Recently, Howard et al. (1998) observed reduced total and ionized serum Mg concentrations in growing kittens fed diets containing 100 mg Mg·kg^{-1}, compared to kittens fed diets with 200 mg Mg·kg^{-1} or higher, DM basis. When the dietary Ca concentration was increased, reduced total and ionized serum Mg concentrations were observed in kittens fed diets containing up to 500 mg Mg·kg^{-1}, although clinical signs, including absence of the blink reflex, were seen only in those fed the diet containing 100 mg Mg·kg^{-1} (Howard et al., 1998). Similarly, Norris et al. (1999) reported no clinical signs of Mg deficiency in adult castrated male cats fed diets containing 100 mg Mg·kg^{-1}, as magnesium sulfate, and 6 g Ca·kg^{-1}.

Freeman et al. (1997) investigated a possible correlation between dietary Mg reduction and hypertrophic cardiomyopathy (HCM) in adult cats. The results suggested that cats with HCM are likely to be fed Mg-restricted (but not Mg-deficient) diets and do not appear to have altered Mg status compared to healthy controls. While cats with HCM had lower urinary creatinine and specific gravity than did controls, no differences in serum creatinine and Mg concentrations, urine Mg concentration and pH, or fractional excretion of Mg were found between cats with HCM and normal cats.

Adverse Effects of Excess Consumption of Magnesium in Cats

As mentioned earlier, there is ample evidence regarding the apparent relationship of excess consumption of Mg to struvite urolithiasis in cats (Lewis et al., 1978; Kallfelz et al., 1980; Lewis and Morris, 1984). Most of these studies were performed using magnesium oxide to increase the Mg concentration from 1.5-2.0 g Mg·kg^{-1} diet, DM basis, the concentration found in commercial cat foods in the 1970s, to 5 g Mg·kg^{-1} diet or higher. Feeding diets containing >1.0 g Mg·kg^{-1} was implicated in increasing the incidence of this metabolic abnormality (Chow et al., 1975; Feldmann et al., 1977; Kallfelz et al., 1980). However, it was subsequently shown that decreasing the urinary pH reduced or prevented formation of struvite uroliths, and cats fed diets inducing an

alkaline urine developed struvite crystals and/or uroliths even at low dietary Mg concentrations (Taton et al., 1984; Buffington et al., 1990). It is now accepted that formulating cat foods to induce a urinary pH of approximately 6.1-6.6 is the most effective means of preventing struvite urolithiasis in this species (Allen et al., 1997). Regardless of the research illustrating that lowering urinary pH is a major factor in reducing the incidence of struvite urolithiasis, the Mg concentration of most contemporary cat foods is generally at or less than 1 g $Mg \cdot kg^{-1}$ diet on a DM basis (Coffman, 1997).

Dietary Magnesium Requirements and Allowances for Cats

Requirements and Allowances for Kittens and Adult Cats

Based on the data of Chausow et al. (1986) and Howard et al. (1998), the minimum dietary Mg requirement of 10-week-old kittens fed purified diets is approximately 160 mg $Mg \cdot kg^{-1}$ in a diet containing approximately 4,000 kcal $ME \cdot kg^{-1}$, assuming normal concentrations of Ca. The MR for an 800-g kitten consuming 180 kcal $ME \cdot d^{-1}$ would thus be 9 mg Mg·kg $BW^{-1} \cdot d^{-1}$ (8.3 mg·kg $BW^{-0.67} \cdot d^{-1}$).

For adult cats the MR can be estimated at 3.1 mg·kg $BW^{-1} \cdot d^{-1}$ (4.9 mg·kg $BW^{-0.67} \cdot d^{-1}$) (Pastoor et al., 1995a). This was determined by balance trials involving the feeding of diets containing 50, 80, 140, and 270 mg Mg per 1,000 kcal ME and evaluating Mg retention. These data showed that the lowest concentration of dietary Mg was sufficient, resulting in close to 0 Mg balance. A diet containing 200 mg $Mg \cdot kg^{-1}$ and 4,000 kcal $ME \cdot kg^{-1}$ would thus provide the MR for a 4-kg adult cat consuming 250 kcal $ME \cdot d^{-1}$. However, since this was the lowest dietary concentration of Mg evaluated in this study, it is possible that the minimum dietary requirement for the adult cat may be even lower.

In these and other experiments, Pastoor et al. (1994a,b; 1995a,b,c) observed apparent absorption of Mg to average 60-80 percent in young kittens, decreasing to 20-40 percent in adult cats, depending on experimental conditions. If the higher value in each case approaches true availability, the RA of Mg could be set at 13 mg·kg $BW^{-1} \cdot d^{-1}$ for kittens and 4 mg·kg $BW^{-1} \cdot d^{-1}$ for adult cats. A diet containing 60 mg per 1,000 kcal ME would provide the RA for both an 800-g kitten consuming 180 kcal $ME \cdot d^{-1}$ and a 4-kg adult cat consuming 250 kcal $ME \cdot d^{-1}$.

However, since Howard et al. (1998) determined that elevated dietary Ca (23 $g \cdot kg^{-1}$) increased the Mg requirement to >100 mg Mg per 1,000 kcal ME of diet for growing kittens, it is prudent to recommend dietary concentrations of 100 mg Mg per 1,000 kcal ME for both kittens and adult cats in order to cover variations in diet that might affect Mg absorption. This would provide 22 mg Mg·kg $BW^{-1} \cdot d^{-1}$ (20 mg·kg $BW^{-0.67} \cdot d^{-1}$) for an 800-g kitten consuming 180 kcal $ME \cdot d^{-1}$ and 6.0 mg·kg $BW^{-1} \cdot d^{-1}$ (9.5 mg·kg $BW^{-0.67} \cdot d^{-1}$) for a 4-kg adult cat consuming 250 kcal $ME \cdot d^{-1}$. These recommendations may represent a better estimate of Mg availability from standard diets.

Requirements and Allowances for Gestation and Lactation in Cats

There is virtually no information on dietary requirements or allowances for Mg in pregnant or lactating queens. Piechota et al. (1995) fed a purified diet containing 104 mg Mg per 1,000 kcal ME to pregnant and lactating queens and found no evidence of Mg deficiency in either the queens or their kittens, showing that this dietary concentration of Mg was sufficient to support these life stages. Such a diet would provide an intake of 14 mg Mg·kg $BW^{-1} \cdot d^{-1}$ (22 mg·kg $BW^{-0.67} \cdot d^{-1}$) to a 4-kg queen nursing four kittens and consuming 540 kcal $ME \cdot d^{-1}$. In the absence of other experimental data, this may be considered the MR of Mg for gestation and lactation. To account for possible lower absorption percentage in standard diets or variations in energy intake, the RA can reasonably be established at 125 mg Mg per 1,000 kcal ME. Such a diet would provide 20 mg Mg·kg $BW^{-1} \cdot d^{-1}$ (32 mg·kg $BW^{-0.67} \cdot d^{-1}$) to a 4-kg cat nursing four kittens in peak lactation and consuming 540 kcal $ME \cdot d^{-1}$.

Safe Upper Limit of Magnesium for Cats

While dietary concentrations higher than approximately 1 g $Mg \cdot kg^{-1}$ on a DM basis had previously been considered to increase the probability of struvite urolithiasis in adult cats, this is no longer thought to be the case unless the pH of the urine is greater than 6.6 (Allen et al., 1997). However, dietary Mg concentrations >1 $g \cdot kg^{-1}$ may still increase the probability of struvite urolithiasis if urinary pH is not carefully controlled and maintained at or below 6.6. Based on the above, the SUL for dietary Mg in cats is highly dependent on urinary pH, and no absolute figure can be provided.

Sodium

Sodium is the tenth most abundant element in the body and the third most abundant cation (after Ca and K) (Lobaugh, 1996). The Na content of the adult mammal is about 1,250 to 1,400 $mg \cdot kg^{-1}$, or about 0.13 percent of BW. Kienzle et al. (1991) for example reported total body Na concentrations of 1.9 $g \cdot kg^{-1}$ in kittens decreasing to 1.4 $g \cdot kg^{-1}$ in adult cats, and Meyer et al. (1985a) measured total body Na content as 2.0 $g \cdot kg^{-1}$ in newborn puppies. Approximately 43 percent of total body Na is found in bone, 29 percent in interstitial fluid, and 12 percent in blood plasma, with the remainder being found in collagenous tissues and as intracellular Na (Briggs et al., 1996). Sodium plays major roles in regulating acid-base balance and extracellular volume because of its importance in the regulation of osmotic pressure. It is also critically important in maintaining the

electrical potential in excitable tissues and in nerve impulse generation and transmission.

Sodium occurs naturally only at very low concentrations in fruits and vegetables, generally significantly less than 1 g $Na \cdot kg^{-1}$, DM basis. In unprocessed meat and milk products, the concentration is higher, perhaps 3 g $Na \cdot kg^{-1}$ or higher on a DM basis. Processed foods, including some meat and cheese products, often contain much higher concentrations of Na (Pennington, 1998). Mineral salts that may contain very high concentrations of Na include sodium chloride (table salt), 39 percent Na; sodium carbonate, 37 percent Na; sodium bicarbonate, 27 percent Na; and monobasic sodium phosphate, 16 percent Na (Table 13-8). Sodium chloride in mineral premixes probably contributes the majority of the Na found in dog and cat foods.

Absorption and Bioavailability of Dietary of Sodium in Dogs

The absorption of dietary Na is generally quite high; in dogs, an apparent absorption of dietary Na close to 100 percent has been observed in several studies (Meyer et al., 1989; Michell, 1989, Hill et al., 2001). However, feeding diets containing significant amounts of soy-derived protein appeared to increase fecal Na output (Meyer et al., 1989; Hill et al., 2001). Meyer et al. (1999) reported that apparent absorption of Na intake in 11 breeds of dogs fed a canned diet averaged only 83 percent. The data of Hill et al. (2001) suggest that a very high proportion, perhaps as much as 80 percent, of dietary Na is absorbed in the colon. Feeding diets with elevated concentrations of cellulose or less digestible forms of carbohydrate such as raw starch has also been shown to decrease apparent absorption of ingested Na, from more than 90 percent in diets with only 1.0 percent cellulose and 2.0 percent carbohydrate to less than 60 percent in diets containing 40 percent raw starch and 20 percent cellulose. The increase in fecal Na content in these studies was directly correlated with the total production of fresh feces (Kienzle et al., 2001).

Sodium Deficiency in Dogs

In a matter of days, Drochner et al. (1976) observed clinical signs of Na deficiency, including restlessness, increased heart rate, water intake, urinary water output, hematocrit, and hemoglobin concentrations and dry and tacky mucous membranes in adult beagle dogs fed diets containing 0.16 g $Na \cdot kg^{-1}$, DM basis, providing 3.6 mg $Na \cdot kg\ BW^{-1} \cdot d^{-1}$. However, Morris et al. (1976) observed no clinical abnormalities in adult German shepherd dogs consuming 4.4 mg $Na \cdot kg\ BW^{-1} \cdot d^{-1}$ with 1.6 $mg \cdot kg\ BW^{-1} \cdot d^{-1}$ from the diet and an additional 2.8 mg $Na \cdot kg\ BW^{-1} \cdot d^{-1}$ from water.

Adverse Effects of Excessive Consumption of Sodium in Dogs

Morris et al. (1976a) reported dietary intakes ranging from 95 to 136 mg $Na \cdot kg\ BW^{-1} \cdot d^{-1}$ in dogs consuming various types of commercial dog foods, which would be equivalent to a maximum of approximately 10 g $Na \cdot kg^{-1}$ diet. Similarly, Allen (1989) found that feeding diets containing 10 g $Na \cdot kg^{-1}$, DM basis, did not increase Ca excretion in normal dogs. Gupta et al. (1981) found no abnormalities in dogs fed 285 mg $Na \cdot kg\ BW^{-1} \cdot d^{-1}$ for periods exceeding 6 weeks. This would be equivalent to a dietary concentration of approximately 18 g $Na \cdot kg^{-1}$. However, this level of Na intake was associated with a significant increase in plasma volume compared to dogs fed 12.6 mg $Na \cdot kg\ BW^{-1} \cdot d^{-1}$ (Gupta et al., 1981). Reinhardt and Behrenbeck (1967) reported negative K balance in adult dogs fed a diet containing approximately 20 g $Na \cdot kg^{-1}$. However, Boemke et al. (1990) found that K balance was reestablished after 2 weeks, albeit at a lower plasma K concentration, in dogs consuming 320 mg $Na \cdot kg\ BW^{-1} \cdot d^{-1}$, representing a dietary concentration of slightly more than 20 g $Na \cdot kg^{-1}$ diet, DM basis. Thus, given adequate availability of water, the normal dog can metabolically adapt to wide variations in Na intake. However, a diet containing an estimated 29 g $Na \cdot kg^{-1}$, DM basis, was reported to be unpalatable and to cause vomiting in adult dogs (Zentek and Meyer, 1995).

Dietary Sodium Requirements and Allowances for Dogs

Requirements and Allowances for Puppies

Few data are available on the dietary Na requirements of growing puppies. The data of Kienzle et al. (1985) and Meyer et al. (1985b) can be used to calculate the Na concentration of milk and the intake of puppies during the fourth week of lactation. Kienzle et al. (1985) reported milk intakes averaging 155 $mL \cdot d^{-1}$ in puppies (of average size adult breeds) at 4 weeks of age. This figure closely matches that observed by Oftedal (1984) in 4-week-old beagle puppies. Meyer et al. (1985b) and Meyer (1984) reported the Na concentration in bitch milk during the fourth week of lactation to be approximately 70 mg per 100 mL. Using these data, Kienzle et al. (1985) estimated Na intake to be approximately 100 $mg \cdot d^{-1}$ (100 $mg \cdot kg\ BW^{-0.75} \cdot d^{-1}$) in 4-week-old puppies weighing approximately 1 kg. This could be considered an AI since data on true availability or different intakes of Na are unavailable. After weaning (if Na and energy requirements are similar, which may somewhat overestimate need), a diet containing 550 mg Na per 1,000 kcal would provide an AI for a 5.5-kg puppy consuming 1,000 kcal $ME \cdot d^{-1}$. This figure is very close to an unpublished value for the dietary Na requirement for growth of puppies (R. D. Kealy, personal communication, 1993).

Requirements and Allowances for Adult Dogs

The minimum Na requirement of the adult dog is approximately 4.4 mg $Na \cdot kg\ BW^{-1} \cdot d^{-1}$ since beagle dogs fed diets containing 3.6 mg $Na \cdot kg\ BW^{-1} \cdot d^{-1}$ developed signs of Na deficiency whereas German shepherd dogs consuming 4.4

mg Na·kg $BW^{-1}·d^{-1}$ did not (Drochner et al., 1976; Morris et al., 1976). This corresponded to dietary Na concentrations of 160 mg·kg^{-1} and 230 mg·kg^{-1} diet, (including Na from water intake), DM basis, respectively. This is in reasonable agreement with Michell (1989) who suggested that the Na requirement for dogs lies between 4.6 and 11.5 mg·kg $BW^{-1}·d^{-1}$, which represented dietary Na concentrations of 300 mg·kg^{-1} and 900 mg·kg^{-1}, DM basis, respectively.

Endogenous fecal loss of Na is quite low. Meyer et al. (1989) in a study of Na absorption as a function of diet type reported that in most cases, Na absorption equaled Na intake. Studies of dogs fed diets containing Na concentrations close to MRs have resulted in measured fecal endogenous Na losses of only about 1.4-1.7 mg·kg $BW^{-1}·d^{-1}$ (Hamlin et al., 1964; Drochner et al., 1976).

Based on the estimates of Morris et al. (1976) and Michell (1989), the minimum Na requirement can be set at approximately 5 mg·kg $BW^{-1}·d^{-1}$ (9.85 mg·kg $BW^{-0.75}·d^{-1}$). A diet containing 75 mg Na per 1,000 kcal ME would thus provide the MR of Na for a 15-kg adult dog consuming 1,000 kcal ME·d^{-1}. With a presumed true absorption of only 40 percent to account for differences in absorption percentage of Na or in energy intake, the RA can be estimated at 13.3 mg·kg $BW^{-1}·d^{-1}$ (26.2 mg·kg $BW^{-0.75}·d^{-1}$). A diet containing 200 mg Na per 1,000 kcal would provide the RA of Na for a 15-kg adult dog consuming 1,000 kcal ME·d^{-1}.

Requirements and Allowances for Gestation and Lactation in Dogs

Using factorial analysis to determine Na allowances for gestation and lactation, Meyer (1985a,b) estimated RAs for Na of 105 and 145 mg·kg $BW^{-1}·d^{-1}$ for gestation and lactation, respectively. The 145-mg Na·kg^{-1} figure set for a medium-sized bitch nursing eight puppies in peak lactation included an estimate of endogenous losses and assumed 75 percent bioavailability. Since the absorption of Na intake is probably greater than 90 percent in most cases and endogenous losses are minimal, the AI may be closer to 80 and 110 mg Na·kg $BW^{-1}·d^{-1}$ (173 and 238 mg·kg $BW^{-0.75}·d^{-1}$) for gestation and lactation, respectively (Meyer et al., 1989; Michell, 1989; Hill et al., 2001). Based on this assumption, the recommended dietary Na concentration for a 22-kg bitch nursing eight puppies would be 500 mg Na per 1,000 kcal ME or 2.0 g Na and 4,000 kcal ME·kg^{-1}. Although the allowance for late gestation would be less, the above diet would be suitable for both gestation and lactation (Meyer et al., 1985a).

Safe Upper Limit of Sodium for Dogs

Zentek and Meyer (1995) fed adult Great Danes and beagle dogs a diet containing an estimated 29 g Na·kg^{-1}, DM basis. This level of Na reduced palatability and caused vomiting in one of the dogs. Based on the data of Reinhardt and Behrenbeck (1967) and Boemke et al. (1990) suggesting that dietary Na concentrations above 20 g·kg^{-1} DM basis result in increased K excretion and negative K balance in adult dogs, the SUL of Na for dogs can reasonably be set at approximately 15 g Na·kg^{-1} diet, DM basis.

Absorption and Bioavailability of Dietary Sodium in Cats

Yu and Morris (1997a) reported apparent absorption of dietary Na intake averaging 75 percent in growing kittens fed diets with with Na concentrations between 0.6 and 2.1 g Na·kg^{-1}, DM basis. In these studies, fecal loss appeared to be constant regardless of dietary Na concentration. Thus, true absorption of Na intake in this study approached 100 percent (Yu and Morris, 1997a). In another study, Yu and Morris (1999b) evaluated Na requirement in adult cats fed diets with concentrations of 0.1-2.0 g Na·kg^{-1}. In this study, as well, fecal Na was constant, suggesting almost 100 percent absorption of Na intake.

Sodium Deficiency in Cats

Clinical signs of Na deficiency (including anorexia, impaired growth, polydypsia, and polyuria) have been described by Yu and Morris (1997a) in 12- to 15-week-old kittens fed a purified diet containing 0.1 g Na·kg^{-1}, DM basis. Metabolic alterations included hemoconcentration, reduced urinary specific gravity, and elevated plasma aldosterone concentrations (Yu and Morris, 1997a). All abnormalities were corrected when the kittens were switched to a diet containing 2.0 g Na·kg^{-1}, DM basis.

Adverse Effects of Excess Consumption of Sodium in Cats

There is no information on the adverse effects of excess consumption of Na in the cat.

Dietary Sodium Requirements and Allowances for Cats

Requirements and Allowances for Kittens

Yu and Morris (1997a) estimated the Na requirements of growing kittens by use of the broken line technique based on plasma aldosterone concentrations. A dietary concentration of 1.6 g Na·kg^{-1} was suggested as the MR. This may overstate the true minimum dietary requirement since an increase in aldosterone is a physiological mechanism to conserve Na and ensure normality at low intakes of this mineral. Given the caloric content of the diet used (5,200 kcal·kg^{-1}), the Na concentration on a caloric basis was 310 mg per 1,000 kcal ME. The requirement for an 800-g kitten consuming 180 kcal ME·d^{-1} is thus 70 mg Na·kg $BW^{-1}·d^{-1}$ (65 mg Na·kg $BW^{-0.67}·d^{-1}$).

Since the use of the aldosterone concentration probably overestimates the minimum Na requirement, a difference between the MR and the RA is probably unnecessary in this case. However, to account for any possible differences in ab-

sorption that may occur as a result of the use of standard diets or circumstances that increase fecal volume, it may be reasonable to include an allowance of 10 percent in assessing the RA (i.e., 1.4 g Na and 4,000 kcal ME·kg^{-1}). This would supply 80 mg Na·kg BW^{-1}·d^{-1} (74 mg·kg BW$^{-0.67}$·d^{-1}) to an 800-g kitten consuming 180 kcal ME·d^{-1}.

Requirements and Allowances for Adult Cats

Extrapolating from a study in kittens, Yu and Morris (1997a) estimated the Na requirement of adult cats fed purified diets to be approximately 21 mg·kg BW^{-1}·d^{-1}. In a subsequent study, the same authors observed the dietary Na requirement in young adult cats to be 160 mg Na per 1,000 kcal ME (Yu and Morris, 1999b). In this study, aldosterone concentration was used to determine the MR, which, as stated previously, probably overstates the MR. Based on these data, however, for a 4-kg cat consuming 250 kcal ME·d^{-1}, the Na requirement is 10 mg Na·kg BW^{-1}·d^{-1} (16.0 mg·kg BW$^{-0.67}$·d^{-1}).

As for kittens, the RA of Na for adult cats may not have to be appreciably higher than the stated MR. This is confirmed by the data of Finco et al. (1989) showing fecal Na losses of 0.8-1.2 mg Na·kg BW^{-1}·d^{-1} in adult cats fed standard diets containing varying sources of P with Na intakes of roughly 15 and 33 mg·kg BW^{-1}·d^{-1}. Apparent absorption of Na was still at least 95 percent. By assuming a minimum percentage Na absorption of 85 percent, the RA for an adult cat would be 10.6 mg Na·kg BW^{-1}·d^{-1} (16.7 mg·kg BW$^{-0.67}$·d^{-1}). A diet containing 170 mg Na per 1,000 kcal ME would provide the RA for a 4-kg adult cat consuming 250 kcal ME·d^{-1}.

Requirements and Allowances for Gestation and Lactation in Cats

There is virtually no information on the dietary Na requirements for gestation in the queen. Since the requirements for gestation are similar to those for growth, a diet that supports the RA of Na for growth should be sufficient. A diet containing 350 mg Na per 1,000 kcal would provide 47 mg Na·kg BW^{-1}·d^{-1} (74.3 mg·kg BW$^{-0.67}$·d^{-1}) for a 4-kg queen in late gestation consuming 540 kcal ME·d^{-1}. This is close to four times the adult maintenance requirement, which should be sufficient.

Regarding lactation, the data of Spray and Widdowson (1950) and Loveridge (1986) may be used to suggest an AI of Na. Queens in peak lactation weighing approximately 3.0 kg and nursing six kittens may require up to 900 kcal ME·d^{-1} to support maintenance and lactation (Loveridge, 1986). However a 4-kg queen nursing four kittens is estimated to consume only approximately 540 kcal ME·d^{-1}, deriving additional energy from body fat (see Chapter 3). The Na content of young kittens has been estimated at 2,300 mg·kg BW^{-1} (Spray and Widdowson, 1950). During the first 6 weeks of life, kittens gain approximately 600 g, or about 100 g per week per kitten (Loveridge, 1986). With four kittens in a litter, 400 g of weight gain will occur per week, which will require 135 mg Na·d^{-1}, in addition to a maintenance requirement of 40 mg·d^{-1}, or a total of 175 mg of bioavailable Na in the diet of the queen. At 95 percent bioavailability, the daily allowance for a 4-kg queen nursing four kittens would be 185 mg Na·d^{-1} or 45 mg Na·kg BW^{-1}·d^{-1}. A diet containing 330 mg Na per 1,000 kcal ME would thus provide the AI of Na for a 4-kg queen nursing four kittens and consuming 540 kcal ME·d^{-1}. This dietary concentration of Na is close to that found by Piechota et al. (1995) to support gestation and lactation in queens.

Dobenecker et al. (1998) however reported that a 4-kg queen at peak lactation nursing four kittens would require approximately 300 mg Na·d^{-1} for milk production. The AI of sodium including maintenance requirements and assuming 95 percent availability would thus be about 90 mg Na·kg BW^{-1}·d^{-1} (142 mg·kg BW$^{-0.67}$·d^{-1}) which would be provided by a diet containing 670 mg Na per 1,000 kcal ME, about twice that of the previous estimate. To assure adequacy, the latter value is best used as the AI.

Safe Upper Limit of Sodium for Cats

There are very few data from which to suggest a SUL for Na intake in growing kittens. In a study of salt preference or appetite in Na-replete or Na-depleted kittens, Yu et al. (1997b) observed behavioral choices of diets containing varying concentration of Na from 0.1 to 10.0 g Na·kg^{-1} diet, DM basis. Both Na-replete and Na-depleted kittens showed an aversion to the diet containing 10 g Na·kg^{-1} when given a choice, but consumed it in normal quantities and without ill effects when it was the only choice. This study also revealed that kittens do not appear to demonstrate the ability to choose Na, when deficient in this mineral, as is common in some other species. Thus, it would appear that as long as adequate water is available, the SUL of dietary Na for kittens is >10 g·kg^{-1}.

It is equally difficult to suggest a SUL for dietary Na in the adult cat. Burger (1979) reported data on water intake of cats fed diets containing varying concentrations of salt. No abnormalities were reported in cats consuming diets containing more than 15 g Na·kg^{-1}. Yet kittens are known to avoid foods containing high concentrations of salt (Yu et al., 1997b). As long as unlimited amounts of water are available, it is likely that cats can tolerate reasonably high concentrations of dietary Na. For adult cats, the SUL for Na is >15 g·kg of diet.

Potassium

Potassium is the eighth most abundant element in the body. It is the second most abundant cation after Ca (Lobaugh, 1996). About 90 percent of body K is present in

intracellular fluid with the remainder being found in bone (7.6 percent), interstitial fluid (1.0 percent), plasma (0.4 percent), and dense connective tissue (1.0 percent) (Tannen, 1996). Total body K concentration in both kittens and adult cats has been reported to be 2.3 $g \cdot kg^{-1}$, while that of newborn puppies is 2.12 $g \cdot kg^{-1}$ (Meyer et al., 1985a; Kienzle et al., 1991b). Potassium serves many functions in the body. It is critically involved in acid-base regulation, in nerve impulse transmission, as a cofactor in enzyme reactions, and in transport functions. Although K concentrations in the major ingredients used in the formulation of dog and cat foods are generally high enough to meet nutrient requirements, several supplemental sources may be used including potassium bicarbonate, 39 percent K; potassium chloride, 57 percent K; and potassium sulfate, 42 percent K (Table 13-8).

Absorption and Bioavailability of Dietary Potassium in Dogs

Like Na, the percentage absorption of K from the intestine of dogs is very high, the apparent absorption of K intake being measured at well over 90 percent in most cases (Meyer et al., 1989; Hill et al., 2001; Kienzle et al., 2001). Unlike Na, K absorption from the small intestine is very high (Hill et al., 2001). Tapioca starch, potato starch, or rice reduced the apparent percentage absorption of K from diets containing these substances in the studies of Meyer et al. (1989). A significant reduction in apparent absorption of K from 95.2 percent in a diet containing 1 percent cellulose, 2 percent carbohydrate, and 35 percent fat to 72 percent in a diet containing 20 percent cellulose, 40 percent raw starch, and 12.6 percent fat has been reported (Kienzle et al., 2001). As with Na, increasing fecal K loss was directly correlated with total output of fresh feces.

Potassium Deficiency in Dogs

Although many reports of the effects of K deficiency on physiologic function in dogs have been published, very few provide data on the dietary K concentrations used in the studies or the K intakes associated with these changes. Feeding a diet that contained about 0.1 g $K \cdot kg^{-1}$ and provided a calculated 4.0 mg K·kg $BW^{-1} \cdot d^{-1}$, Ruegamer et al. (1946a) observed that puppies grew very poorly and, within a few weeks, became restless. During the seventh week, other clinical signs developed including paralysis of the neck muscles, resulting in ventroflexion of the head, followed by paralysis of the rear legs and generalized weakness (Ruegamer et al., 1946a). The dietary K concentration was then increased to 3.35 $g \cdot kg^{-1}$, providing an estimated 130 mg·kg $BW^{-1} \cdot d^{-1}$, whereupon clinical signs disappeared and the growth rate increased dramatically.

Abbrecht (1972) produced hypokalemia in adult bitches by feeding a diet containing 60 mg $K \cdot kg^{-1}$ DM, providing an estimated intake of approximately 0.60 mg·kg $BW^{-1} \cdot d^{-1}$. Although no clinical signs of K deficiency were reported, blood pressure, cardiac output, stroke volume, and renal blood flow decreased progressively with increasing K loss from the body. A diet containing 4.5 g $K \cdot kg^{-1}$ providing an estimated 68 mg K·kg $BW^{-1} \cdot d^{-1}$ fed during a control period was found to be adequate.

Serrano et al. (1964) studied the effect of K intake on pregnant beagle bitches fed diets providing an estimated 220 mg K·kg $BW^{-1} \cdot d^{-1}$ or the same diet without supplemental K, but unfortunately, no total intake values were reported for either diet. No signs of K deficiency were reported in bitches fed the K-depleted diet. At term, both serum and muscle concentrations of K were significantly reduced in bitches fed the K-depleted compared to the normal diet. However, the concentrations of K in the umbilical artery and vein and in the carcasses of the fetuses were no different between the two groups, suggesting that the canine fetus is protected from K depletion of the dam (Serrano et al., 1964).

Adverse Effects of Excess Consumption of Potassium in Dogs

There is virtually no information on the effects of excess consumption of K by dogs. Abnormal clinical effects of excessive consumption of K are unlikely as long as renal function is normal (DiBartola, 2000). Consumption of diets very high in K salts would be likely to cause acute gastroenteritis. Should there be excessive intestinal absorption of K associated with severe hyperkalemia, the major effects would be on the heart, resulting in ventricular fibrillation and cardiac arrest (DiBartola, 2000).

Dietary Potassium Requirements and Allowances for Dogs

Requirements and Allowances for Puppies

Little evidence exists to define dietary K requirements of puppies. Ruegamer et al. (1946a) reversed the effects of K deficiency in puppies by feeding a diet containing an estimated 3.35 g $K \cdot kg^{-1}$ DM, providing an estimated 130 mg K·kg $BW^{-1} \cdot d^{-1}$ to 3- to 4-month-old puppies. Further, using the data of Kienzle et al. (1985) regarding mineral and energy intakes of pre-weaned puppies, an estimate of probable K intake after weaning can be made. Kienzle et al. (1985) suggested that puppies during the fourth week of nursing consume approximately 160 mg K·kg $BW^{-1} \cdot d^{-1}$ and 185 kcal ME·kg $BW^{-1} \cdot d^{-1}$. A 5.5 kg puppy consuming 1,000 kcal ME would have an energy intake of 181 kcal ME·kg $BW^{-1} \cdot d^{-1}$, which is very close to the energy intake predicted for a 4-week-old nursing puppy. The two estimates of energy intake are thus in reasonable agreement.

If a 5.5-kg puppy also requires 160 mg K·kg $BW^{-1} \cdot d^{-1}$, which is in reasonable agreement with the data of Ruegamer et al. (1946a), a diet containing 880 mg K per 1,000 kcal ME should meet this need. While K is almost quantitatively absorbed, a bioavailability of 80 percent is reasonable to cor-

rect for variations in availability and total fecal volume. Thus, the AI of K for a puppy may be estimated to be 200 mg·kg $BW^{-1}·d^{-1}$ and 300 mg·kg $BW^{-0.75}·d^{-1}$ A diet containing 1.1 g K per 1,000 kcal ME would provide the RA for a 5.5-kg puppy consuming 1,000 kcal ME·d^{-1}.

Requirements and Allowances for Adult Dogs

There are no data regarding the MR of K in adult dogs. Dogs used in the study of Abbrecht (1972) remained normal throughout a control period during which they were consuming an estimated minimum of approximately 70 mg K·kg $BW^{-1}·d^{-1}$ (140 mg·kg $BW^{-0.75}·d^{-1}$). This amount of K for a 15-kg dog consuming 1,000 kcal ME·d^{-1} would be supplied by a diet containing 1.0 g K per 1,000 kcal ME.

In previous and subsequent studies, similar intakes of K by adult dogs for 3-6 weeks did not result in any observed clinical or metabolic abnormalities, suggesting that this level of intake is sufficient (Abbrecht, 1969; Patterson et al., 1983). Since no studies have been performed to determine the MRs or RAs of K in diets for adult dogs, the above data must be considered an AI.

Requirements and Allowances for Gestation and Lactation in Dogs

Serrano et al. (1964) fed pregnant bitches a K-deficient diet from the day after mating until 3-4 days before expected whelping. No clinical signs of deficiency were reported, although serum and muscle concentrations of K decreased significantly; however K concentrations in the umbilical blood of pups taken by cesarean section were normal (Serrano et al., 1964). Given normal K status at the time of breeding, bitches can survive gestation and produce normal pups on a K-deficient diet. Other investigators have reported K allowances of 93 and 95 mg·kg $BW^{-1}·d^{-1}$ for pregnant bitches during the last several weeks of pregnancy, based on a presumed availability of 80 percent (Meyer, 1984; Meyer et al., 1985a). Using energy requirements for gestation as recommended in this report (see Chapter 3), 0.9 g K per 1,000 kcal ME can be suggested as the RA of K for gestation.

With respect to lactation, the data of Meyer (1984) and Meyer et al. (1985b) suggest that the dietary allowance of K for a 22-kg lactating bitch nursing eight puppies is approximately 165 mg·kg $BW^{-1}·d^{-1}$, assuming a bioavailability of 80-85 percent. To account for possible difference in energy intake or increase in total fecal output, the RA for K in lactating bitches should be set at 200 mg·kg $BW^{-1}·d^{-1}$ (430 mg·kg $BW^{-0.75}·d^{-1}$). Thus, a diet containing approximately 0.9 g K per 1,000 kcal would provide the RA for a 22-kg bitch nursing eight puppies and consuming 5,000 kcal ME·d^{-1}.

Safe Upper Limit of Potassium for Dogs

There are no data on which to base a SUL for dietary concentrations or intake of K since physiologic mechanisms (e.g., increased urinary excretion) or pathophysiologic mechanisms (e.g., vomiting) generally prevent a life-threatening hyperkalemia should dogs consume excess amounts of this nutrient (DiBartola, 2000). Further, due to poor palatability, dogs are unlikely to consume diets with very high K concentrations.

Absorption and Bioavailability of Dietary Potassium in Cats

Under normal circumstances, dietary K absorption in the cat appears to be quite high. While there appear to be no studies of K absorption in kittens, several studies on adult cats indicate that under normal dietary conditions, apparent absorption of K intake is 90-95 percent or higher (Ching et al., 1989; Finco et al., 1989; Dow et al., 1990) suggesting close to 100 percent true absorption. It is likely that percentage absorption of K intake in kittens is equally as high.

Dow et al. (1990) reported that the addition of 0.8 percent ammonium chloride, DM basis, caused a reduction in apparent absorption percentage of K intake from 95 percent to 80-85 percent in K-restricted adult cats being fed diets with K concentrations of 2 g·kg^{-1}, DM basis. Apparent absorption of K remained reduced, and cats remained in negative K balance, compared to a group not receiving ammonium chloride, for several weeks after the dietary K concentration was increased to 6.6 g·kg^{-1}, DM basis (Dow et al., 1990). On the other hand, Ching et al. (1989) did not observe reduced apparent percentage absorption of K in adult cats fed a K-replete diet (5.5 g K·kg^{-1}) containing 1.5 percent ammonium chloride for a period of 6 months. Although negative K balance was observed, this appeared to be due to increases in urinary loss of K.

Hills et al. (1982) reported that increasing the protein concentration of semipurified diets fed to kittens from normal (33 percent) to high (68 percent) increased the dietary requirement of K from 3 to 5 g·kg^{-1}. However, the increase in K requirement was presumed to be due to changes in renal excretion of K to balance the additional acid load from protein, rather than to its dietary availability (Hills et al., 1982).

Potassium Deficiency in Cats

Deficiency in Kittens

Kittens consuming a 33 percent protein diet with 1.0 or 2.0 g K·kg^{-1} or a 68 percent protein diet with 3.0 or 4.0 g K·kg^{-1} developed clinical signs of K deficiency including anorexia, retarded growth, and neurological disorders beginning as ventroflexion of the head and progressing to ataxia and muscular weakness, which became so severe that the kittens were incapable of walking (Hills et al., 1982). Similarly, clinical signs of K deficiency have been reported in 5-month-old kittens within 2 weeks of being fed a vegetarian diet containing 0.8 or 1.1 g K·kg^{-1}, DM basis, whereas cats

fed similar diets with K added at a concentration of 5.0 $g \cdot kg^{-1}$ remained normal (Leon et al., 1992).

Deficiency in Adult Cats

Dow et al. (1987) reported clinical cases of K deficiency occurring in nine adult cats being fed, on a long-term basis, a commercial diet containing 3.4 g $K \cdot kg^{-1}$, DM basis. A majority of these cats demonstrated elevated serum creatinine concentrations and high fractional excretion percentages of K, signs suggestive of renal disease (Dow et al., 1987). Increasing the K concentration of the diet to 6.5 $g \cdot kg^{-1}$ resulted in a gradual disappearance of clinical and biochemical abnormalities. Subsequently, Dow et al. (1990) evaluated K depletion in adult cats fed diets containing 2.0 g $K \cdot kg^{-1}$ during an 8-week trial. While no clinical abnormalities were observed, plasma K concentrations fell significantly, which were exacerbated by the addition of 0.8 percent ammonium chloride to the diet (Dow et al., 1990). Buffington et al. (1991) also suggested that a relatively low concentration of K, 5.0 $g \cdot kg^{-1}$, in a diet containing somewhat elevated protein (41 percent) fed to adult cats for a period of more than 1 year might be associated with an increased incidence of hypokalemia and renal dysfunction.

Adverse Effects of Excess Consumption of Potassium in Cats

There are no reports of adverse effects associated with excessive consumption of K by cats.

Dietary Potassium Requirements and Allowances for Cats

Requirements and Allowances for Kittens

Hills et al. (1982) reported a minimum K requirement of 3.0 g $K \cdot kg^{-1}$ DM for growth of kittens in a diet containing 33 percent protein and 5.0 $g \cdot kg^{-1}$ DM for kittens fed a diet containing 68 percent protein. The diet containing 33 percent protein contained an estimated 0.67 g K per 1,000 kcal ME and the higher-protein diet, 1.1 g K per 1,000 kcal ME. If a dietary concentration of 0.67 g K per 1,000 kcal ME is the MR for growing kittens, a diet containing approximately 2.7 g $K \cdot kg^{-1}$ and 4,000 kcal $ME \cdot kg^{-1}$ would provide a minimum required K intake of 150 mg·kg $BW^{-1} \cdot d^{-1}$ (140 mg·kg $BW^{-0.67} \cdot d^{-1}$) for an 800-g kitten consuming 180 kcal $ME \cdot d^{-1}$ (if dietary protein content is close to RAs). If diets with significantly higher concentrations of protein are fed, the MR for K will be higher because of increased K needed for anion-cation balance.

The RA should allow for variation in factors such as the metabolic effects of elevated dietary intake of protein or of various salt additives on bioavailability. To ensure normality, an RA of 225 mg K·kg $BW^{-1} \cdot d^{-1}$ (209 mg K·kg $BW^{-0.67} \cdot d^{-1}$) is suggested for the growing kitten. A diet containing 1.0 g K per 1,000 kcal would provide the RA for an 800-g kitten consuming 180 kcal $ME \cdot d^{-1}$.

Requirements and Allowances for Adult Cats

There are insufficient data on which to base a minimum daily requirement of K in adult cats. Feeding adult cats diets with K concentrations ranging from 0.85 to 5 $g \cdot kg^{-1}$ has been associated with clinical and/or metabolic evidence of K deficiency (Dow et al., 1987; Dow et al., 1990; Buffington et al., 1991; Leon et al., 1992). Ching et al. (1989) fed adult cats a standard diet containing 1.5 percent ammonium chloride, 30 percent protein, 5.5 g $K \cdot kg^{-1}$, and an estimated 4,200 kcal $ME \cdot kg^{-1}$ for 6 months. While no clinical signs of K deficiency were observed, the cats were in negative K balance for the first 5 months, returning to slightly positive K balance in the sixth month. Feeding a diet containing 6.6 g $K \cdot kg^{-1}$ and an estimated 4,800 kcal $ME \cdot kg^{-1}$ or 1.4 g K per 1,000 kcal ME reversed all signs of K deficiency in adult cats regardless of the presence of dietary ammonium chloride (Dow et al., 1990).

Currently, many commercial cat foods contain inorganic salts or amino acids that induce an acidic urine (which may increase urinary K excretion) and/or relatively high concentrations of protein (Coffman, 1997). Therefore, the AI of K for adult cats should be set at a concentration that will ensure normality when such diets are fed. Ching et al. (1989) measured K intake of approximately 97 mg·kg $BW^{-1} \cdot d^{-1}$ in cats used in her study. Based on the K concentration of the diet (5.5 $g \cdot kg^{-1}$) and an estimated energy content of 4,200 kcal $ME \cdot kg^{-1}$, this diet contained 1.3 g K per 1,000 kcal. Feeding a diet containing 1.3 g K per 1,000 kcal ME would result in K intakes similar to those of the repletion diet fed to adult cats by Dow et al. (1990), which provided an estimated 80 mg K·kg $BW^{-1} \cdot d^{-1}$ and reversed biochemical signs of K deficiency (Ching et al., 1989; Dow et al., 1990). A diet containing 1.3 g K per 1,000 kcal ME should supply a K intake of 80 mg·kg $BW^{-1} \cdot d^{-1}$ (130 mg·kg $BW^{-0.67} \cdot d^{-1}$) for a 4-kg cat consuming 250 kcal $ME \cdot d^{-1}$, and may be considered the AI for adult cats. It is probable that the MR of K for adult cats is lower than this figure, but determination of the MR requires further experimentation.

Requirements and Allowances for Gestation and Lactation in Cats

There are no reports of minimum dietary K requirements for gestation or lactation in queens. Given normal energy consumption for gestation and lactation, it is probable that diets providing K in amounts recommended for growth should meet the needs of a lactating cat and undoubtedly overestimate the need for late gestation. The AI for a 4-kg queen nursing four kittens might thus be set at 225 mg·kg $BW^{-1} \cdot d^{-1}$, which would be provided by a diet containing 1.7 g K per 1,000 kcal ME. This figure would agree with a factorial estimate combining maintenance needs and an estimated K requirement of 4-week-old nursing kittens of approximately 100 mg $K \cdot d^{-1}$. However, Piechota et al. (1995) reported that a diet containing 1.3 g K per 1,000 kcal ME

supported both gestation and lactation in queens. Based on this, the AI of K for lactating queens weighing 4 kg, nursing four kittens and consuming 540 kcal ME·d^{-1} may be established at 175 mg·kg BW^{-1}·d^{-1} (277 mg·kg $BW^{-0.67}$·d^{-1})

Safe Upper Limit of Potassium for Cats

There are no data available on which to predict a SUL for dietary K intake in cats. Diets containing K concentrations exceeding those recommended above have been fed without reported adverse effects (Buffington et al., 1991). It is unlikely that ill effects due to voluntary intake of excessive amounts of K will occur in cats, as long as free-choice water is available (DiBartola, 2000).

Chloride

Chlorine, in the form of Cl^-, is the most prevalent anion in the extracellular fluid of mammalian species, constituting more than two-thirds of the anions in plasma and extracellular fluid (De Morais, 2000). The mean plasma concentration of Cl^- is about 110 meq·L^{-1} in dogs and 120 meq·L^{-1} in cats, 1 meq constituting 35 mg Cl^-. The intracellular concentration of Cl^- is only 2-4 meq·L^{-1} in most cells, with some exceptions such as the erythrocyte, which can have a Cl^- concentration of 60 meq·L^{-1} or higher. Metabolically, Cl^- is important in maintaining the osmolality of extracellular fluid and in acid-base regulation.

Chloride is found in limited concentrations in most feedstuffs, requiring that many animal diets be supplemented with Cl^--containing salts. Some commonly used sources of Cl^- include ammonium chloride, 66 percent Cl^-; hydrated calcium chloride, 48 percent Cl^-; potassium chloride, 47 percent Cl^-; and sodium chloride, 60 percent Cl^- (Table 13-7). Some vitamin supplements used in petfoods are additional sources of chloride (e.g., choline chloride).

Absorption and Bioavailability of Dietary Chloride in Dogs and Cats

There have been few studies of absorption or bioavailability of Cl^- in either dogs or cats. The apparent absorption of ingested Cl^- decreased from an average of 99 percent in diets containing high (approximately 35 percent) fat, high (approximately 47 percent) cooked starch, or high (approximately 45 percent) raw starch, to approximately 91 percent in dogs as cellulose was increased from 1 to 20 percent, Cl^- absorption being lowest in dogs fed high raw starch and high cellulose (Kienzle et al., 2001). The decrease in apparent absorption of ingested Cl^- in this study was inversely correlated with fecal output (i.e., fecal Cl^- excretion was correlated directly with total fresh feces production).

In one study in adult cats, adding 1.5 percent ammonium chloride to the diet was found to increase apparent absorption of Cl^- intake from approximately 90 to 96 percent in diets containing 5.1 or 16.1 g Cl^-·kg^{-1} diet, DM basis, respectively (Ching et al., 1989). From studies in other species as well, it appears that Cl^- is almost quantitatively absorbed, either actively or passively, in response to the electrical gradient generated by Na transport in both the small and the large intestine (De Morais, 2000).

Chloride Deficiency in Dogs

Only one study of Cl^- deficiency in dogs has been published (Felder et al., 1987). Two-week-old nursing puppies developed clinical and biochemical signs of Cl^- deficiency when fed a milk substitute containing 0.21 g Cl^-·kg^{-1} and an estimated 6,140 kcal ME·kg^{-1} on a DM basis (34 mg Cl^- per 1,000 kcal ME). The pups were fed milk substitute sufficient to provide a caloric intake of approximately 190 kcal ME·kg BW^{-1}·d^{-1}, which resulted in an estimated intake of 6.5 mg Cl^-·kg BW^{-1}·d^{-1}. After being fed the diet for 2 weeks, puppies developed biochemical signs of Cl^- deficiency including hypochloremia, hypokalemia, and metabolic alkalosis. Weight gain ceased, and clinical signs including weakness and ataxia developed, most likely due to the associated K deficiency. Control puppies fed a similar milk substitute supplemented with Cl^- to a concentration of 4.4 g·kg^{-1} (720 mg Cl^- per 1,000 kcal ME), providing an estimated 137 mg Cl^-·kg BW^{-1}·d^{-1}, grew normally and demonstrated no clinical or biochemical abnormalities (Felder et al., 1987).

Adverse Effects of Excess Consumption of Chloride in Dogs

There are no studies of the effects of excess dietary consumption of Cl^- by normal dogs.

Dietary Chloride Requirements and Allowances for Dogs

Requirements and Allowances for Puppies

There have been no studies designed to determine the MR of Cl^- in puppies. Nursing puppies fed a milk substitute containing 4.4 g Cl^-·kg^{-1}, DM basis, grew normally and demonstrated no signs of Cl^- deficiency (Felder et al., 1987). The diet used in this study contained an estimated 6,140 kcal ME·kg^{-1} or 0.72 g Cl^- per 1,000 kcal ME. This would provide approximately 130 mg Cl^-·kg BW^{-1}·d^{-1} (200 mg·kg $BW^{-0.75}$·d^{-1}) to a 5.5-kg puppy consuming 1,000 kcal ME·d^{-1}. Kienzle et al. (1985) recommended a Na intake of 100 mg·kg^{-1} in 4-week-old puppies that, if present entirely as sodium chloride, would represent a Cl^- intake of 150 mg·kg BW^{-1}·d^{-1}, a figure that is in reasonable agreement with that derived by Felder. Again, it is unlikely that all of the Na present is in the form of Cl^- and as with Na, older weaned puppies may have a lower requirement for Cl^- than those that are still nursing. However, in the absence of experimental evidence, the AI of Cl^- for puppies may be set at

0.72 g Cl^-·kg^{-1} for a 4,000 kcal ME·kg^{-1} diet providing 130 mg Cl^-·kg BW^{-1}·d^1 (200 mg·kg $BW^{-0.67}$·d^{-1}).

Requirements and Allowances for Adult Dogs

In the absence of any data on MRs or RAs of Cl^- for adult dogs, an AI can be based only on information relative to the Na requirement. The recommended dietary allowance for Na has been estimated at 13.3 mg·kg BW^{-1}·d^{-1} (Morris et al., 1976b; Michell, 1989). If this is present as sodium chloride, a diet supplying 20 mg Cl^-·kg BW^{-1}·d^{-1} (40 mg·kg $BW^{-0.75}$·d^{-1}) would provide the AI for a 15-kg dog consuming 1,000 kcal ME·d^{-1}. Such a diet should contain 300 mg Cl^- per 1,000 kcal ME.

Requirements and Allowances for Gestation and Lactation in Dogs

There are no data on the Cl^- requirement for gestation/lactation in dogs. Therefore, it may again be prudent to suggest an AI based on Na allowances. Assuming reasonable variation for absorption based on fecal volume, allowances of 110 mg Na·kg BW^{-1}·d^{-1} are recommended for lactation. A diet containing 500 mg Na per 1,000 kcal ME would provide the RA for a 22-kg bitch nursing eight puppies and consuming 5,000 kcal ME·d^{-1}. Based on this, Cl^- intake of 165 mg·kg BW^{-1}·d^{-1} and 358 mg·kg $BW^{-0.75}$·d^{-1}, which would represent the AI of Cl^- for a 22-kg bitch nursing eight puppies and consuming 5,000 kcal ME·d^{-1}, could be met by a diet containing 750 mg Cl^- per 1,000 kcal ME. Such a diet would most likely exceed the Cl^- requirement of a similar-sized bitch in late gestation.

Safe Upper Limit of Chloride for Dogs

The SUL for dietary Na concentrations in diets for dogs is approximately 15 g Na·kg^{-1} diet, DM basis (Reinhardt and Behrenbeck, 1967; Boemke et al., 1990). If this is present as sodium chloride, in the absence of other data, the SUL for dietary Cl^- in normal dogs might be set at 22.5 g Cl^-·kg^{-1}, DM basis. However it is unlikely that all dietary Na is in this form. Some calculolytic diets for dogs currently may contain as much as 23.4 g Cl^-·kg^{-1}, DM basis. Although these diets are not considered complete and balanced for long-term feeding, this is due primarily to factors other than Na and Cl^- concentrations. Thus, at present time, the SUL for dietary Cl^- of 23.5 g·kg^{-1} diet may be reasonable for dogs.

Chloride Deficiency in Cats

Chloride deficiency has recently been described in kittens. Serum chemical abnormalities and some clinical signs of deficiency were observed in kittens fed diets containing 0.1, 0.4, or 0.7 g Cl^-·kg^{-1} (Yu and Morris, 1999a). These clinical signs were attributable to a secondary K deficiency (Simopoulos and Bartter, 1980; Yu and Morris, 1998). Chloride deficiency results in a decrease of Na absorption from the loop of Henle, resulting in increased Na concentration in renal tubular fluid reaching the distal tubule of the kidney, wherein the reabsorption of Na is accompanied by an exchange for K, promoting excess K excretion (Simopoulos and Bartter, 1980). Kittens fed diets containing 1.0 g Cl^-·kg^{-1} or higher did not develop signs of Cl^- deficiency (Yu and Morris, 1998, 1999a).

Adverse Effects of Excess Consumption of Chloride in Cats

There is little published evidence on adverse effects of excess dietary consumption of Cl^- by cats. Several studies have been performed in which diets with Cl^- concentrations of 11.4-16.0 g·kg^{-1} have been fed to both kittens and cats (Ching et al., 1989; Pastoor et al., 1994d,c). Feeding Cl^- at concentrations of at least 11.4 or 11.8 g·kg^{-1} diet, as the calcium salt, to kittens and adult cats, respectively, providing intakes of more than 140 mg Cl^-·kg BW^{-1}·d^{-1}, did not result in adverse effects (Pastoor et al., 1994d; Pastoor et al., 1994c). On the other hand, Ching et al. (1989) reported reduced or negative Ca and K balances in adult cats fed a diet containing 16 g Cl^-·kg^{-1} diet (approximately 250 mg Cl^-·kg BW^{-1}·d^{-1}), mainly as the ammonium salt during a 5-month feeding trial. However, the negative Ca and K balances may have been due to the greater degree of metabolic acidosis that occurred when diets were supplemented with ammonium compared to calcium chloride (Pastoor et al., 1994c).

Dietary Chloride Requirements and Allowances for Cats

Requirements and Allowances for Kittens

Based on the study of Yu and Morris (1999a), the minimal Cl^- requirement in the diet of kittens is 1.0 g Cl^-·kg^{-1} diet, DM basis. The purified diet used in these studies contained 0.19 g Cl^- per 1,000 kcal ME which may be considered the MR of Cl^- for kittens. Based on these data, the MR of an 800-g kitten consuming 180 kcal ME·d^{-1} would be 45 mg Cl^-·kg BW^{-1}·d^{-1} (42 mg·kg $BW^{-0.67}$·d^{-1}).

Dietary Cl^- is very highly available (Ching et al., 1989); however, it may be prudent to account for possible variability in absorption of Cl^- or energy intake when standard diets are being fed. The RA for dietary Cl^- in kittens may thus be set at 50 mg·kg BW^{-1}·d^{-1} (46.5 mg·kg $BW^{-0.67}$·d^{-1}) for an 800-g kitten consuming 180 kcal ME·d^{-1}. This would be supplied by a diet containing approximately 225 mg Cl^- per 1,000 kcal ME.

Requirements and Allowances for Adult Cats

No studies have been reported of minimal dietary Cl^- requirements for adult cats. In the absence of experimental data, the recommended dietary Cl^- allowance for kittens

(0.9 g Cl^-·kg^{-1}, and 4,000 kcal ME·kg^{-1}) may be used as the basis for setting the adequate dietary concentration of Cl^- for the adult cat as well. Such a diet would provide an AI of approximately 15 mg Cl^-·kg BW^{-1}·d^{-1} (23.7 mg·kg $BW^{-0.67}$·d^{-1}) for a 4-kg adult cat consuming 250 kcal ME·d^{-1}. This is identical to the amount of Cl^- that would be recommended if the RA of Na for adult cats were used as the basis for determining Cl^- need (Yu and Morris, 1999b).

Requirements and Allowances for Gestation and Lactation in Cats

No information is available on the Cl^- requirement for gestation and lactation in the cat. Therefore, it is reasonable to base Cl^- recommendations on those for Na. This may overestimate true need since all Na may not be present as Cl^-, therefore, the recommendation must be considered an AI. For gestation the AI of Na is 47 mg Na·kg BW^{-1}·d^{-1}. The equivalent intake of Cl^- would be 70 mg Cl^-·kg BW^{-1}·d^{-1} (111 mg·kg $BW^{-0.67}$·d^{-1}). A diet containing 520 mg Cl^- per 1,000 kcal ME would provide the AI for a 4-kg queen in late gestation consuming 540 kcal ME·d^{-1}. This figure may significantly overestimate the actual chloride needs for gestation.

For a lactating queen, the RA of Na is 90 mg·kg BW^{-1}·d^{-1}.The equivalent intake of Cl^- would be 135 mg·kg BW^{-1}·d^{-1} (213 mg·kg $BW^{-0.67}$·d^{-1}). A diet containing 1.0 g Cl^- per 1,000 kcal ME would supply the RA for a 4-kg queen nursing four kittens and consuming 540 kcal ME·d^{-1}.

Safe Upper Limit of Chloride for Cats

There are no reported studies of dietary Cl^- toxicity in cats. While feeding a diet containing 16.1 g Cl^-·kg^{-1} as the ammonium salt has been reported to result in negative Ca and K balance, this effect was probably due more to the relative metabolic acidosis and subsequent reduced urinary pH caused by ammonium chloride than to the concentration of dietary Cl^- (Ching et al., 1989). If Cl^- is present in the diet mainly in the form of neutral salts, it is probable that reasonably high concentrations can be tolerated and no SUL can be defined.

TRACE MINERALS

The trace mineral content of common petfood ingredients is listed in Table 13-6.

Iron

Iron is the most prevalent trace mineral in the animal body, comprising about 0.005 percent of total weight. Meyer (1984) reported the Fe content in newborn and young adult dogs to be 76 and 100 mg·kg BW^{-1} respectively, while in both newborn and young adult cats, Fe content has been reported to be 50-60 mg·kg BW^{-1} (Kienzle et al., 1991b). Approximately 67 percent of Fe is found in hemoglobin, 27 percent in macrophages, 4 percent in muscle as myoglobin, and the remainder in various enzymes, with a small amount in the labile Fe pool. The primary role of Fe is in the synthesis of hemoglobin and myoglobin where it functions as a transporter and binder of oxygen. However, it also functions in a number of enzyme systems (e.g., cytochromes) that are important in energy metabolism (Fairbanks, 1994).

While milk is a poor source of Fe, many other ingredients used in dog and cat foods are rich in Fe. This includes meat meals, meat and bone meals, many cereal grains, and even major mineral supplements such as dicalcium phosphate. In addition to the Fe present in animal source ingredients, many dog and cat foods include an Fe source as a supplement. Some commonly used sources of Fe in dog and cat foods are steamed bone meal, 2.8 percent Fe; dicalcium phosphate, 1.4 percent Fe; and ferrous sulfate heptahydrate, 21.8 percent Fe (Table 13-9). Iron oxide and carbonate demonstrate negligible bioavailability and should not be used as dietary sources of Fe (AAFCO, 2001).

Absorption and Bioavailability of Dietary Iron in Dogs and Cats

Iron is present in dog and cat foods in two forms: inorganic Fe and organically bound Fe, mainly in the form of heme. Intestinal absorption of inorganic Fe is inversely related to Fe status, to the dietary concentration of Fe, and to the dietary concentrations of several other nutrients such as Ca, P, Zn, and Cu (Erdman, 1979; Fernandez and Phillips, 1982; Kochanowski and McMahan, 1990; Gross et al., 2000). Calcium supplements, for example, have been shown to decrease the apparent absorption of Fe intake in human diets from 20 percent to 5-10 percent under various conditions (Hallberg et al., 1991). Various fiber sources such as psyllium and pectin have also been shown to reduce the apparent percentage absorption of inorganic Fe intake (Erdman 1979; Fernandez and Phillips, 1982). Ferrous iron is more bioavailable than the ferric form, and certain inorganic sources of Fe such as iron oxide or carbonate have very poor bioavailability. The apparent percentage absorption of ingested heme iron, on the other hand, has only been shown to be negatively affected by increasing dietary Ca; Hallberg et al. (1991) showed that the apparent absorption of heme iron intake was reduced from 15-20 percent to 10 percent in humans fed beef without or with a Ca supplement, respectively.

The apparent bioavailability of Fe in a standard dry-type diet fed to pregnant and lactating bitches has been estimated to be 30 percent (Meyer et al., 1985a,b). Hill et al. (2001) reported that apparent absorption of ingested Fe in adult dogs from diets containing various percentages of beef and soy protein ranged from 6.2 to 14.8 percent. On the other hand, Frost et al. (1940), based on studies in puppies fed milk diets

supplemented with Fe in the form of ferric chloride, reported apparent absorption of ingested Fe as high as 70 percent and suggested true absorption may approach 100 percent. Ruegamer et al. (1946b) also reported apparent absorption of ingested Fe, in the form of ferric pyrophosphate, from diets fed to puppies to be 60 percent or higher. Thus, it appears that the absorption and bioavailability of Fe in dogs, and presumably also in cats, can vary enormously, from close to 100 percent to less than 10 percent depending on the ionic form of Fe in the diet, Fe status, dietary Fe concentration, and several other factors.

Iron Deficiency in Dogs

Chausow and Czarnecki-Maulden (1987) found that weanling puppies consuming diets containing less than approximately 80 mg Fe·kg^{-1} (3.3 mg Fe·kg BW^{-1}·d^{-1}) developed signs of Fe deficiency including suboptimal blood hemoglobin concentration and low hematocrit values. Clinical signs reported in Fe deficiency in dogs include poor growth, pale mucous membranes, lethargy, weakness, diarrhea, hematochezia, and melena (Harvey, 1998). Hematological changes include a microcytic hypochromic anemia and a low percentage saturation of plasma transferrin. While there are no reports on which to base a dietary concentration or daily intake that would result in Fe deficiency signs in adult dogs, the data of Meyer et al. (1985a) and Hill et al. (2001) suggest that this would be well below an intake of 1 mg Fe·kg BW^{-1}·d^{-1} assuming reasonable bioavailability.

Adverse Effects of Excessive Consumption of Iron in Dogs

Free Fe in the body is extremely reactive, catalyzing oxidative reactions that can lead to tissue damage. When only a small amount of Fe is ingested it is firmly bound to proteins such as apoferritin, transferrin, and hemosiderin in enterocytes, plasma, and storage sites such as macrophages. Iron resulting from hemoglobin degradation is efficiently reutilized but is virtually always present in protein-bound form. However, the total binding capacity of all such proteins is small and can be overwhelmed by intake of larger amounts of Fe, resulting in the presence of toxic amounts of free Fe in the system.

There are very few studies of toxic effects in dogs of excess Fe included in foods. However, there are reports of toxic effects of Fe acutely administered enterally by capsule administration, gavage, or forced feeding. D'Arcy and Howard (1962) found that oral doses of ferrous sulfate providing as little as 12 mg Fe·kg BW^{-1}·d^{-1} resulted in mild gastrointestinal damage identified at necropsy. Acute doses of 600 mg Fe·kg BW^{-1} were fatal. Bronson and Sisson (1960) found that acute doses of ferrous sulfate, as low as 200 mg Fe·kg BW^{-1}·d^{-1}, administered directly into the jejunum were fatal within 6 hours. Reissman and Coleman (1955) found that doses of ferrous sulfate (250 mg Fe·kg BW^{-1}) were fatal within 5 to 7 hours when administered by stomach tube or directly into the duodenum. The absorption of Fe in the aforementioned studies was most likely very high, perhaps greater than 60 percent, as previously noted in dogs fed Fe as a supplement in a milk diet (Frost et al., 1940).

Dietary Iron Requirements and Allowances for Dogs

Requirements and Allowances for Puppies

Initial studies of Fe requirements of puppies suggested, based on hemoglobin response, that approximately 600 µg Fe·kg BW^{-1}·d^{-1} maintained normal growth of puppies as long as the Fe was in a readily bioavailable form such as ferric pyrophosphate (Ruegamer et al., 1946b). Chausow and Czarnecki-Maulden (1987) determined that the minimal requirement of Fe for puppies was 84 mg Fe·kg^{-1} diet, DM basis. Based on caloric content, this can be expressed as 18 mg Fe per 1,000 kcal ME. The report provided data on food intake, which indicated that Fe consumption at this dietary concentration averaged 3.3 mg Fe·kg BW^{-1}·d^{-1} (5.0 mg·kg BW$^{-0.75}$·d^{-1}). Although the bioavailability of dietary Fe was not measured in these studies based on the type of diet it presumably was reasonably high (Ruegamer et al., 1946b; Chausow and Czarnecki-Maulden, 1987). To allow for lower bioavailability of Fe in standard diets, the RA of Fe is suggested to be 4.0 mg·kg BW^{-1}·d^{-1} (6.1 mg·kg BW$^{-0.75}$·d^{-1}). A diet containing 22 mg Fe per 1,000 kcal ME would supply this amount of Fe for a 5.5-kg puppy consuming 1,000 kcal ME·d^{-1}.

Requirements and Allowances for Adult Dogs

There is very little available information on the Fe requirement of adult dogs, which can undoubtedly vary a great deal depending on many factors. By use of factorial analysis, Meyer et al. (1985b) suggested that the RA of Fe for mature bitches is 0.36 mg·kg BW^{-1}·d^{-1}. This recommendation included an estimate of 30 percent bioavailability of ingested Fe and might be considered a RA. To account for variability in absorption, a bioavailability of only 20 percent might be reasonable, raising the AI or RA to 0.50 mg Fe·kg BW^{-1}·d^{-1}. Hill et al. (2001) reported apparent absorption of ingested Fe, averaging 9.2 percent, with an average apparent absorption of 0.30 mg Fe·kg BW^{-1}·d^{-1} in adult dogs. True percentage absorption of Fe was probably higher, but given the reasonably high Fe content of the diets (250 mg Fe·kg^{-1}), it is possible that total Fe absorption exceeded the requirement. Nonetheless these data are in reasonable agreement with those of Meyer. If 0.50 mg Fe·kg BW^{-1}·d^{-1} (1.0 mg·kg BW$^{-0.75}$·d^{-1}) is considered the AI for Fe, a diet containing 7.5 mg Fe per 1,000 kcal ME would provide this amount for a 15-kg adult dog consuming 1,000 kcal ME·d^{-1}.

Requirements and Allowances for Gestation and Lactation in Dogs

Meyer et al. (1985a), using a factorial approach, recommended a daily allowance of 2.6 mg Fe·kg $BW^{-1}·d^{-1}$ for pregnant bitches assuming the bioavailability of Fe to be 30 percent. In medium-sized lactating bitches nursing six puppies, a diet providing 2.6 mg Fe·kg $BW^{-1}·d^{-1}$ was also suggested, again assuming a bioavailability of 30 percent. To allow for variations in diet and energy intake, a bioavailability of only 20 percent should be assumed (i.e., 4 mg Fe·kg $BW^{-1}·d^{-1}$ or 8.67 mg·kg $BW^{-0.75}·d^{-1}$). A diet containing approximately 17 mg Fe per 1,000 kcal ME would thus provide the RA of Fe for a 22-kg bitch in late gestation or peak lactation nursing eight puppies and consuming 5,000 kcal ME·d^{-1}.

Safe Upper Limit of Iron for Dogs

While D'Arcy and Howard (1962) observed that acute doses of 50 mg Fe·kg $BW^{-1}·d^{-1}$ resulted in signs of hemorrhage and ulceration in the gastrointestinal tract of dogs, presumably this Fe was given as an acute dose to fasted dogs and thus may not be comparable to Fe availability in dogs being fed standard diets. Other investigators have reported the effects of Fe toxicity in dogs, but, in these studies as well, Fe was administered parenterally or given by gavage as acute doses (Hoppe et al., 1955a; Reissman and Coleman, 1955; Brown et al., 1959; Bronson and Sisson, 1960). Therefore, these data do not allow conclusions regarding a SUL of dietary Fe. Since there are no studies of Fe toxicity in dogs being fed standard diets, no recommendations as to a SUL of Fe in dogs can be made.

Iron Deficiency in Cats

There is only one literature report of Fe deficiency in cats. Chausow and Czarnecki-Maulden (1987) found that feeding diets containing less than 80 mg Fe·kg^{-1} to weanling kittens resulted in abnormally low blood hemoglobin and hematocrit levels. Splenic Fe concentration was also maximized at a dietary Fe concentration of 80 mg·kg^{-1}, DM basis (Chausow and Czarnecki-Maulden, 1985, 1987). The clinical signs of Fe deficiency in cats are similar to those reported for dogs (i.e., pale mucous membranes, lethargy, weakness, weight loss or lack of weight gain, hematuria, melena) (Harvey, 1998).

Adverse Effects of Excessive Consumption of Iron in Cats

Hoppe et al. (1955b) estimated the LD_{50} (median lethal dose) of an acute oral dose of Fe in the form of ferrous sulfate heptahydrate to be greater than 500 mg·kg BW^{-1}. Hoppe et al. (1955a) found that acute oral doses of Fe (16-128 mg Fe·kg BW^{-1}) as ferrous sulfate or ferrous gluconate resulted in vomiting within 1 hour of administration. As in dogs, most studies of Fe toxicity in cats have involved administration of acute doses that may have little relevance to Fe concentrations in standard diets.

Dietary Iron Requirements and Allowances for Cats

Requirements and Allowances for Kittens and Adult Cats

The data of Chausow and Czarnecki-Maulden (1985, 1987) showed that a dietary Fe concentration of 80 mg·kg^{-1} of diet (17 mg per 1,000 kcal ME) was necessary for normal Fe metabolism in weanling kittens fed purified diets. The data allowed a determination of Fe intake, which averaged 3.42 mg·kg $BW^{-1}·d^{-1}$ (3.2 mg·kg $BW^{-0.67}·d^{-1}$). The diets used in these studies were also phytate- and fiber-free, and a highly bioavailable source of Fe was used, suggesting that this is a minimum daily requirement. When standard diets are fed, a higher concentration of Fe would likely be indicated. Similarly, Harper et al. (2000) fed canned diets containing approximately 19 mg Fe per 1,000 kcal ME (approximately 3.85 mg Fe·kg $BW^{-1}·d^{-1}$) and observed normal growth and development, hematological and clinical parameters remaining within normal limits during the 10-week feeding trial. To allow for possible reduced bioavailability of Fe in dry-type diets, as well as for variations in energy intake, the RA is suggested to be 4.5 mg Fe·kg $BW^{-1}·d^{-1}$ (4.2 mg·kg $BW^{-0.67}·d^{-1}$). A diet containing 20 mg Fe per 1,000 kcal would thus meet the recommended Fe allowance for an 800-g kitten consuming 180 kcal ME·d^{-1}.

There are no available data on Fe requirements or RAs for adult cats. In their absence, a diet containing sufficient Fe for growth is recommended as providing an AI of Fe for the adult cat. In such a case, the Fe intake of a 4-kg adult cat consuming 250 kcal ME·d^{-1} would be 1.25 mg Fe·kg $BW^{-1}·d^{-1}$ (1.98 mg·kg $BW^{-0.67}·d^{-1}$).

Requirements and Allowances for Gestation and Lactation in Adult Cats

There is virtually no information on which to base Fe intake recommendations for gestation and lactation in cats. Extrapolating from data in dogs and a determination of milk production and Fe content in the milk of lactating queens, depending on litter size and time after queening, a factorial approach assuming 20 percent bioavailability of dietary Fe suggests an adequate Fe intake for lactating cats of about 3 mg·kg $BW^{-1}·d^{-1}$ (Meyer et al., 1985b; Dobenecker et al., 1998). Piechota et al. (1995) found that a diet containing 20 mg Fe per 1,000 kcal ME supported gestation and lactation in queens. On this basis, the AI of Fe for a 4-kg cat in late gestation or lactation nursing four kittens and consuming 540 kcal ME·d^{-1} would be 2.7 mg Fe·kg $BW^{-1}·d^{-1}$ (4.3 mg·kg $BW^{-0.67}·d^{-1}$).

Safe Upper Limit of Iron for Cats

There are no available data on which to base a SUL of dietary Fe for cats.

Copper

The bodies of dogs and cats contain a very small amount of Cu. Meyer (1984) reported total body content of Cu to be 3.8 and 7.3 mg·kg BW^{-1} for newborn and young adult dogs, whereas Kienzle et al. (1991b) reported values of 2-3 mg Cu·kg BW^{-1} in both kittens and adult cats. The majority of the body pool of Cu is found bound to metallothionein in the liver. In food and fiber animals (e.g., cattle, horses, sheep, goats), liver Cu content is frequently used as an indicator of Cu status of the animal. After intestinal absorption, Cu is transported to the liver bound to plasma albumin. In the liver, it becomes bound to ceruloplasmin, a Cu-containing δ-globulin that is secreted into the plasma and becomes the major circulating form of Cu.

Copper is an integral component of enzymes that catalyze oxidation reactions. These include monoamine oxidase, lysyl oxidase, ferroxidase, and cytochrome C oxidase. Physiologically, Cu serves many functions. For example, lysyl oxidase plays an important role in connective tissue formation. By virtue of its role in ferroxidase enzymes, Cu is involved in Fe metabolism and hematopoiesis. It is also essential through its role in tyrosinase for melanin pigment formation and thus for normal hair color. Through its role in cytochrome oxidase, it is involved in myelin formation and other aspects of central nervous system function, as well as in oxidative phosphorylation. As a cofactor of the enzyme superoxide dismutase, Cu also is critical for appropriate defense mechanisms against oxidative damage (Turnlund, 1994).

Copper is not found in high concentrations in many of the ingredients used in the manufacture of petfoods. The bran and germ portions of grains are reasonable sources of Cu, containing up to 20 mg Cu·kg^{-1}. Animal liver may contain similar concentrations of Cu on a wet weight basis, although there are reports that the Cu present in some animal liver (e.g., pork liver) may not be bioavailable (Aoyagi and Baker, 1993a). Therefore, Cu is frequently added as a supplement to petfoods. Several Cu supplements are available including cupric chloride, 37.2 percent Cu; cupric sulfate pentahydrate, 25.4 percent Cu; cupric oxide, 80 percent Cu; and cuprous oxide, 89 percent Cu (Table 13-9). However, many animal studies, including some of dogs and cats, have demonstrated that cupric oxide is only very slightly bioavailable and therefore should not be used as a Cu supplement in petfoods (Aoyagi and Baker, 1993b; Czarnecki-Maulden et al., 1993; Fascetti et al., 1998). In one study, a Cu-lysine complex was shown to have bioavailability similar to that of cupric sulfate, suggesting that such complexes may be usable as supplemental sources of Cu (Baker et al., 1991).

Absorption and Bioavailability of Dietary Copper in Dogs and Cats

Other than the studies mentioned above, there is little information on bioavailability of dietary Cu in dogs and cats. Based mainly on clinical signs and histopathologic findings, a recent report suggested the existence of a Zn-induced dietary Cu deficiency in kittens (Hendriks et al., 2001). However, there is ample evidence from studies in other species of factors that may affect bioavailability of Cu. Excessive dietary concentrations of Fe or Zn decrease the bioavailability of Cu (Turnlund, 1994). Zinc is a potent inhibitor of Cu bioavailability by virtue of its stimulation of the formation of metal-binding metallothionein proteins in enterocytes, which have a higher binding affinity for Cu than for Zn. Phytate, however, does not seem to seriously affect Cu absorption (Graf, 1986). There are few data on apparent or true percentage absorption of ingested Cu in dogs or cats. In studies of the nutrient needs of pregnant and lactating bitches, Meyer (1984) and Meyer et al. (1985a,b) reported an estimated Cu bioavailability of 30 percent. Morris and (Fascetti 2000), from data in rats and humans, suggested that the bioavailability of Cu may be quite high (i.e., from 55 to 75 percent).

Copper Deficiency in Puppies and Dogs

There are few published data on Cu deficiency in puppies or adult dogs. In one study, a group of 5-week-old puppies fed a diet containing 0.2 mg Cu per 1,000 kcal of digestible energy (DE) developed a loss of hair pigmentation after 4 months and hyperextension in the distal phalanges (Zentek and Meyer, 1991), suggesting that this concentration was insufficient to support growth and resulted in Cu deficiency in puppies. Czarnecki-Maulden et al. (1993) observed that feeding diets containing 1.1 or 1.9 mg Cu per 1,000 kcal ME (copper sulfate) to puppies resulted in reduced serum Cu concentrations. Copper deficiency has been suspected or reported in other studies, but dietary information was not included (Hartley et al., 1963; Gumbrell, 1972; Meiser and Schulz, 1997; Uchida et al., 1997).

Adverse Effects of Excess Consumption of Copper in Dogs

Gubler et al. (1953) administered an acute oral dose of 165 mg Cu (as copper sulfate)·kg BW^{-1} to dogs. This resulted in vomiting and death within four hours. Total plasma copper rose from a normal concentration of ~100 mg/dL to 850 µg/dL within 40 minutes of copper administration and then decreased gradually until death.

There is a considerable body of evidence on Cu toxicosis in several breeds of dogs with a suspected or proven hereditary defect resulting in excessive accumulation of Cu in the liver, including Bedlington terriers, West Highland white terriers, and Skye terriers (Twedt et al., 1979; Johnson et al.,

1982; Su et al., 1982; Thornburg et al., 1986;). The disease has been studied predominantly in Bedlington terriers (Twedt et al., 1979; Ludwig et al., 1980; Su et al., 1982; Brewer, 1998). Liver Cu concentrations in affected dogs may reach several thousand micrograms per gram compared to a normal of up to several hundred micrograms per gram (Ludwig et al., 1980). It was initially thought that the disease in dogs may be a model for Wilson's disease in humans, but more recent work has shown that in dogs the disease is caused by a different gene than that for Wilson's disease, even though it is also due to a defect in biliary excretion of Cu (Brewer, 1998). Anticopper therapies such as Zn supplementation and orally administered tetrathiomolybdate have been used for treatment of the problem in dogs, as well as feeding special diets with reduced concentrations of Cu (Brewer et al., 1992).

Dietary Copper Requirements and Allowances for Dogs

Requirements and Allowances for Puppies and Adult Dogs

Evaluating Cu deficiency in weanling puppies, Zentek and Meyer (1991) found that 2.5 mg Cu per 1,000 kcal ME, when fed in an available form such as cupric sulfate, provided an AI of Cu for growing puppies. Subsequently, Czarnecki-Maulden et al. (1993) measured Cu availability and requirement in groups of puppies fed canned (standard) diets and found that puppies fed diets containing 2.7 mg Cu per 1,000 kcal ME as cupric sulfate remained normal. This suggests that 2.7 mg Cu per 1,000 kcal ME may be taken as a dietary RA for the growing puppy (Czarnecki-Maulden et al., 1993). Such a diet would supply 0.5 mg Cu·kg BW^{-1}·d^{-1} (0.76 mg·kg $BW^{-0.75}$·d^{-1}) for a 5.5-kg puppy consuming 1,000 kcal ME·d^{-1}.

There are very few data on the Cu requirements of adult dogs. By extrapolating from factorial data on mineral requirements of pregnant and lactating bitches, the RA for maintenance can be estimated at 0.1 mg Cu·kg BW^{-1}·d^{-1} (0.2 mg·kg $BW^{-0.75}$·d^{-1}), assuming an apparent bioavailability of Cu of 30 percent (Meyer, 1984; Meyer et al., 1985a). A diet containing 1.5 mg Cu per 1,000 kcal ME would provide this amount to a 15-kg adult dog consuming 1,000 kcal ME·d^{-1}.

Requirements and Allowances for Gestation/Lactation in Dogs

Meyer (1984) and Meyer et al. (1985a,b) have reported recommended Cu allowances for bitches during gestation and lactation. For gestation a daily allowance of 0.16 mg Cu·kg BW^{-1}·d^{-1} was suggested and, for lactation, 0.70 mg Cu·kg BW^{-1}·d^{-1} (1.52 mg·kg $BW^{-0.75}$·d^{-1}), assuming 30 percent availability of Cu in each case (Meyer, 1984; Meyer et al., 1985a,b). A diet containing 3.1 mg Cu per 1,000 kcal ME or 12.4 mg Cu·kg^{-1} and 4,000 kcal ME·kg^{-1} would provide sufficient Cu for a 22-kg bitch in late gestation or nursing eight puppies and consuming 5,000 kcal ME·d^{-1}.

Safe Upper Limit of Copper for Dogs

As mentioned previously, acute Cu toxicity has been produced experimentally in the dog, and a hereditary disorder resulting in excess Cu storage has also been described in certain breeds. However there is no available information on a SUL of dietary Cu in normal dogs.

Copper Deficiency in Kittens and Cats

Doong et al. (1983) observed that kittens fed diets containing less than 1.0 mg Cu per 1,000 kcal ME demonstrated Cu deficiency as evidenced by decreased weight gain and low liver concentrations of Cu compared to kittens fed diets with higher Cu content. However, no other clinical or postmortem signs of Cu deficiency were consistently noted, although histologic sections of lung and aorta appeared morphologically immature in some kittens fed the basal diet with the lowest concentration of Cu (0.12 mg per 1,000 kcal ME). While no biochemical data were available, based on clinical signs of fading coat color and hind-limb ataxia and on histopathologic changes, Hendriks et al. (2001) reported a suspected case of Cu deficiency induced by overconsumption of Zn by 4- to 5-month-old kittens housed in cages with galvanized iron door bars (Hendriks et al., 2001). However, other investigators have questioned the validity of this suggestion (J. G. Morris, and A. Fascetti, personal communication, 2002).

In adult queens, Fascetti et al. (1998, 2000) reported an effect of Cu intake on reproductive efficiency, specifically the time between exposure to a tom and conception, in queens that had consumed a Cu-deficient ration for 4 months. Queens fed purified diets containing 0.8 or 1.2 mg Cu per 1,000 kcal ME demonstrated an increased time to conceive compared to queens fed a diet containing 2.2 mg Cu per 1,000 kcal ME. In all cases, Cu was supplied by cupric sulfate. In one of these reports, cats fed diets containing approximately 2 mg Cu·kg^{-1} as cupric oxide had an even longer time to conception, demonstrating that Cu from cupric oxide has very poor bioavailability (Fascetti et al., 1998, 2000).

Adverse Effects of Excess Consumption of Copper in Cats

There are no reports of adverse effects of excess consumption of dietary Cu by normal cats.

Dietary Copper Requirements and Allowances for Cats

Requirements and Allowances for Kittens and Cats

Based primarily on weight gain, Doong et al. (1983) estimated the daily dietary RA of Cu for weanling kittens to be

between 0.9 and 1.1 mg per 1,000 kcal ME. However, both liver and serum concentrations of Cu were higher in kittens fed diets containing 2.1 mg Cu per 1,000 kcal ME. The concentrations of Cu in the liver and serum of kittens fed a diet containing 2.1 mg Cu per 1,000 kcal ME were similar to those found in adult cats fed a normal ration before a Cu depletion study (Fascetti et al., 1998). Based on these data the MR of dietary Cu for normal growth in kittens may be set at approximately 1.1 mg per 1,000 kcal ME. Such a diet would provide a Cu intake of 0.25 mg·kg $BW^{-1}·d^{-1}$ (0.23 mg·kg $BW^{-0.67}·d^{-1}$) to an 800-g kitten consuming 180 kcal ME·d^{-1}. Since the MR for growth does not appear to normalize all metabolic parameters and to account for possible variations in bioavailability from standard diets, the RA of dietary Cu (in an available form such as sulfate) for growing kittens may be set at 2.1 mg Cu per 1,000 kcal ME. This diet would provide a daily intake of 0.47 mg Cu·kg $BW^{-1}·d^{-1}$ (0.44 mg·kg $BW^{-0.67}·d^{-1}$) to an 800-g kitten consuming 180 kcal ME·d^{-1}.

With respect to adult cats, Fascetti et al. (1998, 2000) reported that purified diets containing 1.2 mg Cu per 1,000 kcal ME, as the sulfate, when fed to queens after a period of Cu depletion, resulted in normal blood and liver concentrations of Cu. Feeding this level of Cu also resulted in a reduced number of days until conception in breeding queens compared to feeding diets containing 0.6 mg Cu as the sulfate per 1,000 kcal ME or 2.0 mg Cu as cupric oxide per 1,000 kcal ME (Fascetti et al., 1998, 2000). Based on these data, a dietary concentration of 1.2 mg Cu per 1,000 kcal ME may be used as an AI for the adult cat. A 4-kg queen consuming 250 kcal ME·d^{-1} would have an AI of 0.075 mg Cu·kg $BW^{-1}·d^{-1}$ (0.119 mg·kg $BW^{-0.67}·d^{-1}$).

Requirements and Allowances for Gestation and Lactation in Cats

With respect to gestation, Fascetti et al. (1998, 2000) fed adult queens purified dry diets containing 0.8, 1.2, or 2.2 mg Cu per 1,000 kcal ME of diet as cupric sulfate. The shortest time for conception after exposure of queens in estrus to a tom was 16 days in those fed diets containing 2.2 mg Cu per 1,000 kcal ME, but there was no significant difference between the means for gestation onset in queens fed diets containing 1.2 or 2.2 mg Cu per 1,000 kcal ME (Fascetti et al., 1998, 2000).

The data of Doong et al. (1983) and of Fascetti et al. (1998, 2000) suggest that pregnant queens fed diets containing concentrations of Cu ranging from 0.6 to 12 mg·kg^{-1} (0.1-2.4 mg per 1,000 kcal ME), even after several months on a Cu depletion diet, produced normal kittens with normal plasma and liver concentrations of Cu. Further, the data of Doong et al. (1983) suggest that queens being fed a low-Cu diet can successfully nurse litters of kittens. This implies that liver Cu stores are sufficient to support the needs of reproducing queens for considerable periods of time during which a Cu-deficient diet is being fed. Based on data for growing kittens and adult cats (Fascetti et al., 1998, 2000) and in the absence of specific experimental data, it seems reasonable to recommend as an AI a diet containing 2.2 mg Cu per 1,000 kcal ME for gestation and lactation, assuming that the dietary Cu has a bioavailability similar to that of cupric sulfate. A 4-kg queen in late gestation or nursing four kittens and consuming 540 kcal ME·d^{-1} would thus have an AI of 0.30 mg Cu·kg $BW^{-1}·d^{-1}$ (0.47 mg·kg $BW^{-0.67}·d^{-1}$). This figure is in excellent agreement with a factorial approach to the recommended Cu intake of a 4-kg queen nursing four kittens using the data of Dobenecker et al. (1998) and Keen et al. (1982) for milk production and milk Cu concentration and a presumed Cu bioavailability of 30 percent in a similar sized queen nursing four kittens during the fourth week of lactation.

Safe Upper Limit of Copper for Cats

There are no available data on which to predict a SUL of dietary Cu for cats.

Zinc

Zinc is a transition metal with an atomic weight of 65.4 and a valence of +2. It is found throughout the body, mainly as an intracellular constituent, but is present in most tissues in relatively low concentrations. Meyer (1984) measured total body Zn content of newborn puppies and young adult dogs as 23.1 and 9.5 mg·kg BW^{-1}, wet weight, respectively, while Kienzle (1991) reported total body Zn concentrations of 18 mg·kg BW^{-1} in newborn kittens increasing to 30 mg·kg BW^{-1} in young adults, on a wet weight basis. Zinc has many essential functions in the body acting as a cofactor or catalyst in some 200 Zn-containing enzymes that are involved in cell replication, carbohydrate and protein metabolism, skin function, and wound healing. Zinc is also thought to play a crucial role in the structure and function of biological membranes as well as in the stabilization of DNA and RNA. Zinc is absorbed mainly in the small intestine. During digestion, it is generally converted to its ionic form where it can form complexes with various inorganic and organic ligands, such as amino acids, phosphate, sulfate, and so forth. Zinc-amino acid complexes, (e.g., with methionine or lysine), have been reported to be as bioavailable as many inorganic forms of Zn such as zinc sulfate in many species.

The sources of Zn in petfoods are quite varied. Animal sources, particularly beef products and other red meats as well as whole grains, are reasonably good sources of Zn. Leguminous plants are also good Zn sources. Nonetheless, most petfoods are supplemented with Zn including zinc carbonate, 52.1 percent Zn; zinc chloride, 48 percent Zn; zinc oxide, 78 percent Zn; and zinc sulfate monohydrate, 36.4 percent Zn (Table 13-9).

Absorption and Bioavailability of Dietary Zinc in Dogs and Cats

The absorption of dietary Zn is largely a function of other substances in the diet that alter its bioavailability. Most animal products and seafood are relatively free of constituents that interfere with Zn absorption, and, as mentioned previously, amino acids derived from meat digestion may actually improve the absorption of Zn. Vegetable products are more likely to contain chemicals that interfere with Zn absorption, the most notable of these being phytate; phytate is present in many plant sources including cereals such as corn, wheat, and rice and oilseed meals such as soy, peanut, and sesame, which may contain 1.5 percent or more phytate (Erdman, 1979). Dietary phytate has long been known to reduce the absorption of Zn, and this effect is exacerbated by high concentrations of dietary Ca (Graf, 1986). High concentrations of dietary Mg may also enhance the effect of phytate on Zn bioavailability, but this effect is not as great as that of Ca. Phytate is known to bind Zn more strongly than it does Cu or Mn (Morris and Rogers, 1994). Although Baker (1995) has reported that high amounts of Cu and Fe can reduce the absorption and/or bioavailability of Zn, the amounts required to do this would be unlikely to be found in standard petfoods. There is some evidence that extrusion cooking may inhibit the degradation of dietary phytic acid in the gut, compared to other cooking methods, resulting in less efficient absorption of Zn in extruded petfoods (King and Keen, 1994).

Ozpinar et al. (2001) reported apparent Zn absorption of 25 to 34 percent in puppies. This study showed that apparent absorption of Zn appeared highest when zinc sulfate was the source of supplemental Zn. Further, it suggested that the apparent absorption of Zn decreased with increasing dietary Zn intake and perhaps also with age, although this could not be proven because of study design (Ozpinar et al., 2001). Meyer (1984) estimated bioavailability of Zn to be 25 percent in pregnant and lactating bitches. However, in subsequent studies, Zn bioavailability of 40 percent was suggested for pregnant and lactating bitches (Meyer et al., 1985a,b).

Although several other investigators have reported data on the bioavailability of Zn, none of these studies provided data on fractional intestinal absorption. However, using other physiologic parameters such as hair growth, hair Zn concentration, and plasma Zn concentration to evaluate bioavailability of various Zn compounds, a number of investigators have reported that Zn-amino acid, Zn-polysaccharide, or Zn-propionate complexes are more bioavailable than zinc oxide (Brinkhaus et al., 1998; Lowe et al., 1994; Lowe and Wiseman, 1998). On the other hand, Wedekind and Lowry (1998) suggested that Zn in the form of zinc-propionate is probably no more available than Zn in the inorganic form of zinc sulfate. These studies suggest that zinc oxide may not be the preferred form for supplemental Zn. However Baker (1995) reported the bioavailability of Zinc oxide to be similar to that of zinc sulfate in swine.

There are no reports of absorption or bioavailability of dietary Zn in cats.

Zinc Deficiency in Puppies and Dogs

There are a few reports of experimentally induced Zn deficiency in puppies and dogs. Robertson and Burns (1963) observed that puppies (age not stated) fed a standard diet containing 33 mg $Zn \cdot kg^{-1}$ and 11 g $Ca \cdot kg^{-1}$ developed signs of Zn deficiency, including decreased serum concentrations of Zn-requiring enzymes and total serum Zn. Signs of Zn deficiency were not seen in dogs fed diets containing 3.0 g $Ca \cdot kg^{-1}$ and 33 mg $Zn \cdot kg^{-1}$ or in dogs fed diets containing 11 g $Ca \cdot kg^{-1}$ and 133 mg $Zn \cdot kg^{-1}$ (Robertson and Burns, 1963).

Subsequently, Sanecki et al. (1982, 1985) produced Zn deficiency in weanling Pointer puppies by feeding a dry standard type diet containing 20-35 mg $Zn \cdot kg^{-1}$ (11 mg Zn per 1,000 kcal ME) and 26.4 g $Ca \cdot kg^{-1}$, DM basis, providing 2.0 mg $Zn \cdot kg\ BW^{-1} \cdot d^{-1}$. Puppies fed this amount of Zn developed clinical signs of Zn deficiency including very poor growth rates and significant skin lesions, which began in areas of contact or wear such as foot pads. Control puppies fed the same diet but supplemented to a concentration of 120 mg $Zn \cdot kg^{-1}$ (as zinc carbonate; 39 mg Zn per 1,000 kcal ME; 7.3 mg $Zn \cdot kg\ BW^{-1} \cdot d^{-1}$) grew normally and demonstrated no clinical signs of Zn deficiency.

In addition to experimental studies of Zn deficiency, there have been a number of reports of naturally occurring Zn deficiency syndromes in dogs (Ohlen and Scott, 1986; Van Den Broek and Thoday, 1986; Sousa et al., 1988; Van Den Broek and Stafford, 1988; Colombini, 1999; Colombini and Dunstan, 1997). This appears to occur in two forms. One of them is a syndrome occurring in northern breed dogs (e.g., Alaskan huskies or Malamutes) that is due to a genetic defect resulting in interference with Zn absorption. Treatment requires lifelong supplementation of the diet with significant quantities of Zn (Colombini and Dunstan, 1997). The second syndrome has occurred in many breeds as well as in mongrels, frequently, but not always, in young growing dogs (Ohlen and Scott, 1986; Van Den Broek and Thoday, 1986; Sousa et al., 1988; Van Den Broek and Stafford, 1988; Huber et al., 1991). In this manifestation, clinical and biochemical signs of Zn deficiency may occur because of feeding dogs foods that are low in Zn. In one such report, Zn deficiency was diagnosed in 60 puppies being fed a commercial dry diet containing 35-40 mg $Zn \cdot kg^{-1}$ (Ohlen and Scott, 1986). More commonly it has been reported in growing dogs being fed cereal-based, low-quality petfoods containing high concentrations of substances that bind Zn (Huber et al., 1991; Sousa et al., 1988; Van Den Broek and Thoday, 1986). The clinical and biochemical findings in such reports have been virtually

identical to those described in experimental cases of Zn deficiency, and, in all cases, affected animals have responded promptly to Zn supplementation or a change to a diet with a higher bioavailability of Zn.

Adverse Effects of Excess Consumption of Zinc in Dogs

Zinc is a relatively nontoxic substance, and dietary deficiencies of this nutrient are more likely to occur than are dietary excesses (Gross et al., 2000). A few cases of inadvertent excess consumption of Zn by individual dogs, mainly puppies, have been reported in the literature (Hornfeldt and Koepke, 1984; Breitschwerdt et al., 1986; Torrance and Fulton, 1987; Latimer et al., 1989), but these were clinical observations of single animals not in controlled experiments with control and test subjects. In all these cases of excess Zn consumption (e.g., from ingestion of metallic objects made of Zn), clinical signs have included acute gastroenteritis, hemolytic anemia, and lethargy.

Dietary Zinc Requirements and Allowances for Dogs

Requirements and Allowances for Puppies

The studies of several investigators, as noted earlier, have shown that feeding standard diets containing 33-45 mg $Zn \cdot kg^{-1}$ to growing dogs of several breeds resulted in clinical and biochemical evidence of Zn deficiency, particularly when the Ca concentration of the diet was above 10 $g \cdot kg^{-1}$ (Robertson and Burns, 1963; Sanecki et al., 1982; 1985; Ohlen and Scott, 1986). Interestingly, Robertson and Burns (1963) found no difference between the Zn status of dogs fed diets containing only 3 g $Ca \cdot kg^{-1}$ and 33 mg $Zn \cdot kg^{-1}$ and those fed diets containing 11 g $Ca \cdot kg^{-1}$ and 133 mg $Zn \cdot kg^{-1}$. Both groups maintained normal Zn status. Booles et al. (1991) fed purified diets containing 50 or 200 mg $Zn \cdot kg^{-1}$ and 13 g $Ca \cdot kg^{-1}$ to Labrador retriever puppies during the growth phase; normal growth and plasma Zn parameters were reported in all puppies. They suggested that purified diets containing 50 mg $Zn \cdot kg^{-1}$ maintained normal Zn status when fed to growing puppies. However, the source of the Zn used in this study was not specified.

The studies of Sanecki et al. (1982, 1985) showed that puppies fed standard-type diets containing 20-35 mg $Zn \cdot kg^{-1}$ and 26.4 g $Ca \cdot kg^{-1}$ developed Zn deficiency, while pups fed similar diets with 120 mg $Zn \cdot kg^{-1}$ remained normal. The preponderance of available data suggests that the Ca concentration of the diet has a significant effect on Zn bioavailability, with the dietary Zn requirement being remarkably lower in diets containing relatively low concentrations of Ca. Further, other dietary constituents, such as phytate, can significantly reduce Zn availability (Graf, 1986).

Based on the data of Robertson and Burns (1963) and Booles et al. (1991), including corrections for energy content of the diets used, the dietary MR of Zn for puppies may be set at 10 mg Zn per 1,000 kcal. This would provide a minimum Zn requirement of 1.8 mg $Zn \cdot kg\ BW^{-1} \cdot d^{-1}$ (2.7 mg $\cdot kg\ BW^{-0.75} \cdot d^{-1}$) for a 5.5-kg puppy consuming 1,000 kcal $ME \cdot d^{-1}$. This requirement assumes a reasonably low dietary concentration of Ca.

However, based on the data of Sanecki (1982, 1985) the dietary Zn concentration may have to be as high as 40 mg per 1,000 kcal ME to prevent deficiency signs in diets containing high concentrations of Ca ($\geq$26 $g \cdot kg^{-1}$). It is unlikely that contemporary standard diets for puppies would contain this high a concentration of Ca. However, to account for variations in bioavailability of Zn such as higher dietary concentrations of Ca ($\geq$10 $g \cdot kg^{-1}$) or phytate, the dietary RA is reasonably set at 25 mg Zn per 1,000 kcal ME (Robertson and Burns, 1963; Sanecki et al., 1982, 1985). The RA of Zn for a 5.5-kg puppy consuming 1,000 kcal $ME \cdot d^{-1}$ would thus be 4.5 mg $\cdot kg\ BW^{-1} \cdot d^{-1}$ (6.84 mg $\cdot kg\ BW^{-0.75} \cdot d^{-1}$).

Requirements and Allowances for Adult Dogs

Hill et al. (2001) fed adult hound dogs four canned diets averaging 25.7 mg Zn per 1,000 kcal ME (1.9 mg $Zn \cdot kg\ BW^{-1} \cdot d^{-1}$) and 20 g $Ca \cdot kg^{-1}$ for a total of 12 weeks with no signs relating to Zn deficiency reported. Apparent availability of Zn was indistinguishable from zero, suggesting negligible net absorption (i.e., endogenous loss was equivalent to true absorption, but no data on endogenous losses were reported). Also, in adult dogs, Meyer (1984) and Meyer et al. (1985a) reported the RA of Zn for adult maintenance to be 1.0 mg $Zn \cdot kg\ BW^{-1} \cdot d^{-1}$, based on an estimated bioavailability of 25 percent. Based on these data, an AI of Zn for adult dogs may be set at approximately 1.0 mg $Zn \cdot kg\ BW^{-1} \cdot d^{-1}$ (2.0 mg $\cdot kg\ BW^{-0.75} \cdot d^{-1}$). A diet containing 15 mg Zn per 1,000 kcal ME would provide the adequate Zn intake for a 15-kg adult dog consuming 1,000 kcal $ME \cdot d^{-1}$.

Requirements and Allowances for Gestation and Lactation in Dogs

Recommended daily allowances of Zn for gestation and lactation in dogs have been reported to be 1.22 mg and 2.7 mg $Zn \cdot kg\ BW^{-1} \cdot d^{-1}$, respectively (Meyer et al., 1985a,b); in both cases the bioavailability of Zn was assumed to be 40 percent. However, other studies suggest that the bioavailability of Zn in dogs may be lower, i.e., as low as 20 percent in puppies (Meyer, 1984; Ozpinar et al., 2001). Assuming bioavailability of 20 percent, the allowances would increase to 2.44 and 5.4 mg $Zn \cdot kg\ BW^{-1} \cdot d^{-1}$ (5.2 and 11.7 mg $\cdot kg\ BW^{-0.75} \cdot d^{-1}$), respectively, which may be more reasonable. A diet containing 24 mg Zn per 1,000 kcal ME would thus provide an AI of Zn for a 22-kg bitch in late gestation or nursing eight puppies and consuming 5,000 kcal $ME \cdot d^{-1}$.

Safe Upper Limit of Zinc for Dogs

Drinker et al. (1927) fed dogs diets containing up to 80 mg Zn·kg $BW^{-1}·d^{-1}$ in the form of zinc oxide for several months without ill effects. However, in the same study, cats showed no adverse effects of consuming more than 200 mg Zn·kg $BW^{-1}·d^{-1}$, so the value for dogs is unlikely to represent a SUL. As mentioned previously, although there are several reports of Zn toxicity in individual dogs, none of these reports provide information on total Zn intake (Hornfeldt and Koepke, 1984; Breitschwerdt et al., 1986; Torrance and Fulton, 1987; Latimer et al., 1989). Therefore, there is insufficient information available on which to base a SUL of dietary Zn for dogs.

Zinc Deficiency in Kittens and Cats

There is very little information on Zn deficiency in kittens or cats. In a brief report, Aiken et al. (1978) reported skin lesions and growth retardation in young kittens fed a vegetable-based diet containing 40 mg $Zn·kg^{-1}$. However, neither the source of the Zn, the concentration of Ca, nor the concentration of other constituents of the diet was provided. Kane et al. (1981) fed kittens a soy-based basal diet containing 8.0 g $Ca·kg^{-1}$ and two concentrations of Zn as sulfate. Groups were fed the basal diet with 15 mg $Zn·kg^{-1}$, 15 mg Zn plus 6 additional g $Ca·kg^{-1}$ or 67 mg $Zn·kg^{-1}$. During an 8-month trial, all kittens developed normally but kittens fed the lower concentration of Zn had reduced serum Zn concentrations. Histopathologic evaluation of the testicles from male kittens fed diets containing 15 mg $Zn·kg^{-1}$ demonstrated significant degeneration of the seminiferous tubules. The testicular damage resulting from feeding the low-Zn diet for 8 months was not reversed after 8 weeks of feeding the diet containing 67 mg $Zn·kg^{-1}$ (Kane et al., 1981).

In a second experiment, groups of weanling kittens were fed diets containing 0.7, 52, and 4.8 mg $Zn·kg^{-1}$ (EDTA-washed soy protein or crystalline amino acids as the protein source) for a period of 8 weeks (Kane et al., 1981). Kittens fed the diet containing soy and 0.7 mg $Zn·kg^{-1}$ grew very slowly for 3 weeks and then began to lose weight. Kittens fed the diet containing soy and 52 mg $Zn·kg^{-1}$ grew linearly in a manner similar to those in the first experiment and gained almost 20 $g·d^{-1}$. Kittens fed the amino acid diet containing 4.8 mg $Zn·kg^{-1}$ had intermediate weight gains between the two other groups. Plasma Zn concentrations in kittens fed the diets containing 0.7 or 4.8 mg $Zn·kg^{-1}$ were similar (50 and 40 $\mu g·dL^{-1}$, respectively), while those in kittens fed the diet containing 52 mg $Zn·kg^{-1}$ averaged 90 $\mu g·dL^{-1}$, which is very similar to the kittens fed diets containing 67 $mg·kg^{-1}$ in the first experiment. Two of three kittens fed the diet containing 0.7 mg $Zn·kg^{-1}$ and one kitten fed the amino acid diet with 4.8 mg $Zn·kg^{-1}$ developed perioral skin lesions compatible with parakeratosis. Liver Zn concentrations were also reduced in kittens fed the two lower concentrations of Zn.

Adverse Effects of Excess Consumption of Zinc in Cats

There are no reports on adverse effects of excess consumption of zinc by cats.

Dietary Zinc Requirements and Allowances for Cats

Requirements and Allowances for Kittens and Cats

The experiments of Aiken et al. (1978) and Kane et al. (1981) provide some information on which to base an AI of Zn for kittens and cats. It is unknown why dietary Zn concentrations of only 15 $mg·kg^{-1}$ resulted in normal growth in the experiments of Kane et al. (1981), whereas kittens fed diets with 40 mg $Zn·kg^{-1}$ failed to grow normally in the studies of Aiken (1978). However, differences in the form of Zn used and the presence of competing dietary factors such as phytate and Ca may have been involved. Further, although feeding diets containing 15 mg $Zn·kg^{-1}$ supported normal growth in kittens, such concentrations were not sufficient to prevent testicular lesions (Kane et al., 1981).

It would appear that diets containing Zn at concentrations of 67 $mg·kg^{-1}$ support normal growth and normal liver Zn status in kittens and cats (Kane et al., 1981). The data of Kane et al. (1981) show that kittens fed diets with this concentration of Zn grew from an average of 800 to 2,000 g during the course of the 8-week study and food consumption averaged 55 $g·d^{-1}$. The diet contained approximately 12.5 mg Zn per 1,000 kcal ME, which may be considered a dietary MR. This would provide a Zn intake of 2.8 mg Zn·kg $BW^{-1}·d^{-1}$ (2.6 mg·kg $BW^{-0.67}·d^{-1}$) to an 800-g kitten consuming 180 kcal $ME·d^{-1}$.

To allow for variations in bioavailability and energy intake it would seem prudent to include a safety factor of 50 percent and set the RA of Zn at 18.5 mg Zn per 1,000 kcal ME. The RA of Zn for an 800-g kitten consuming 180 kcal $ME·d^{-1}$ would thus be 4.2 mg·kg $BW^{-1}·d^{-1}$ (3.9 mg·kg $BW^{-0.67}·d^{-1}$).

Since there are no available data on Zn requirements of adult cats, the above values may be recommended as the AI for maintenance of adult cats as well. Therefore, a 4-kg adult cat consuming 250 kcal $ME·d^{-1}$ of a diet containing 18.5 mg Zn per 1,000 kcal ME would have an AI of 1.2 mg Zn·kg $BW^{-1}·d^{-1}$ (1.9 mg·kg $BW^{-0.67}·d^{-1}$).

Requirements and Allowances for Gestation and Lactation in Cats

Little information is available on Zn requirements or allowances for gestation or lactation in cats. Piechota et al. (1995) showed that a purified diet with a Zn concentration

of approximately 10.5 mg per 1,000 kcal ME supported gestation and lactation in queens. This is very close to the MR of Zn for growth of kittens and may be assumed to be the MR for this life stage. This would provide a Zn intake of 1.4 mg Zn·kg $BW^{-1}·d^{-1}$ (2.2 mg·kg $BW^{-0.67}·d^{-1}$) for a 4-kg queen nursing four kittens and consuming 540 kcal $ME·d^{-1}$.

Kienzle (1998) reported that queens nursing four kittens produced about 8 percent of BW per day of milk with a Zn concentration of 730 µg per dL. Using a factorial approach with an assumption of 25 percent bioavailability a RA of 3.4 mg Zn·kg $BW^{-1}·d^{-1}$ was suggested (Kienzle, 1998). However, based on the findings of Piechota et al. (1995) it is likely that the bioavailability of Zn may well be higher and/or the actual requirement may be lower than that calculated by Kienzle. Therefore, it seems prudent to set the RA of Zn for gestation and lactation at approximately 2.0 mg Zn·kg $BW^{-1}·d^{-1}$ (3.2 mg·kg $BW^{-0.67}·d^{-1}$). If this is the case, a diet containing 15 mg Zn per 1,000 kcal ME would provide the dietary RA for a 4-kg queen nursing four kittens and consuming 540 kcal $ME·d^{-1}$.

Safe Upper Limit of Zinc for Cats

Drinker et al. (1927) fed cats diets providing up to 230 mg Zn (as zinc oxide)·kg $BW^{-1}·d^{-1}$ for several months and did not report any adverse effects. Sterman et al. (1986) fed adult cats a diet containing 600 mg $Zn·kg^{-1}$ for 6 weeks during a study to determine the effects of dietary Zn intake on kindled seizure induction in cats (Sterman et al., 1986). The blood Zn concentrations in these cats rose to 120 µg·dL^{-1} compared to an average of 90 µg·dL^{-1} in cats fed a similar diet that contained 100 mg $Zn·kg^{-1}$. No other information on the composition of the diet was provided, but no clinical abnormalities were reported. This would suggest that the SUL of dietary Zn for adult cats, at least for short periods of time, is >600 $mg·kg^{-1}$.

Manganese

Manganese occurs in only very small amounts in animal tissues. Extrapolating from human data, an adult dog may have a total body content of only about 3-15 mg Mn (Hurley and Keen, 1987). Hendricks et al. (1997) found the total body content of Mn in cats weighing 4 kg to be approximately 2.3 mg. Manganese has been reported to be reasonably evenly distributed throughout the tissues with perhaps somewhat higher concentrations in bone and liver. It functions mainly as an essential structural component in metalloenzymes (e.g., arginase, pyruvate carboxylase, and manganese superoxide dismutase) or, more commonly, as a metallic activator, either specifically or nonspecifically, of many other enzymes such as hydrolases, decarboxylases, kinases, and transferases (Hurley and Keen, 1987). At the tissue level, Mn is known to be important for normal bone development and neurologic function. Petfood ingredients that contain reasonable quantities of Mn include cereal grains and animal, poultry, and seafood products. Nonetheless, supplementary Mn is frequently added to petfoods, mainly in the form of inorganic salts. Some of these are manganese carbonate, 47.8 percent Mn; manganese chloride, 43 percent Mn; manganese oxide, 60 percent Mn; and manganese sulfate monohydrate, 32.5 percent Mn (Table 13-9).

Absorption and Bioavailability of Dietary Manganese in Dogs and Cats

There are no reports of absorption or bioavailability of Mn in dogs or cats, but, in other species, manganese sulfate and chloride demonstrate similar bioavailability, manganese-methionine or protein chelates are a bit higher, while manganese oxide and manganese carbonate have lower bioavailability (Henry, 1995). In a report on mineral requirements of bitches and suckling pups, Meyer (1984) estimated the bioavailability of dietary Mn, including absorption efficiency, to be 10 percent. In studies in rats, cattle, and humans, determinations of apparent absorption of ingested Mn have ranged from 3-4 percent in adults to 20 percent in younger individuals (Hurley and Keen, 1987; Henry, 1995). On the other hand, Henry (1995) reported retention of from 75 to 90 percent of radiolabeled Mn from milk. From studies in other species it is known that excessive Fe or Ca can negatively affect the bioavailability of Mn, but there are no quantitative data on such interactions in dogs and cats. Therefore, dietary Mn concentrations and Mn intake can be based only on the assumption of normal dietary concentrations of competing nutrients.

Manganese Deficiency in Dogs and Cats

There are no clinical or experimental reports of Mn deficiency in dogs or cats. However, from studies in other mammals, it appears that Mn deficiency is manifested in newborn or growing animals by retarded bone growth and shortening and bowing of the forelegs, and in adult animals by lameness and/or enlarged joints, poor locomotor function, and ataxia, all of which appear to be due to inhibition of endochondral osteogenesis. A specific joint abnormality in newborn sheep, goats, and cattle, known as arthrogryposis, may occur as the result of Mn deficiency, although other etiologic agents can cause this problem (Radostits et al., 2000). These bone and joint abnormalities including the classical slipped tendon or "perosis" of poultry, appear to be due to improper bone matrix formation as a result of dysfunction of Mn-containing enzymes required for normal cartilage formation and turnover (Hurley and Keen, 1987). Manganese deficiency has also been reported to have profound negative effects on reproduction, including delayed estrus, poor conception, increased abortion rates, stillbirths, and low birth rates.

Adverse Effects of Excess Consumption of Manganese in Dogs and Cats

There are no reports of toxic effects of excess consumption of Mn in dogs or cats.

Dietary Manganese Requirements and Allowances for Dogs

Requirements and Allowances for Puppies and Adult Dogs

There are no specific reports regarding dietary requirements or allowances of Mn for puppies. However, from data on the concentration of Mn in bitch milk and the weight and consumption of milk by nursing puppies, an AI of Mn by puppies can be proposed (Lonnerdal et al., 1981; Oftedal, 1984; Kienzle et al., 1985). At peak lactation in beagles, Oftedal (1984) reported milk consumption of 175 mL per pup per day by puppies weighing 1.2 kg. Lonnerdal et al. (1981) reported Mn concentration of milk during peak lactation to be 0.15 $\mu g \cdot mL^{-1}$ on an as-fed basis. Based on these data, the Mn intake of nursing puppies during peak lactation would be 22 μg Mn·kg $BW^{-1} \cdot d^{-1}$. On the other hand, from milk intake data, Kienzle et al. (1985) estimated the Mn intake of nursing puppies to be 50 $\mu g \cdot kg\ BW^{-1} \cdot d^{-1}$. These puppies had a reported energy intake of 185 kcal ME·kg $BW^{-1} \cdot d^{-1}$ (Kienzle et al., 1985).

Although the two estimates are in reasonable agreement, for safety purposes a value of 35 μg Mn·kg $BW^{-1} \cdot d^{-1}$ is suggested. Further, it is likely that the bioavailability of ingested Mn from milk is much higher (approximately 80 percent) than that from standard diets (Henry, 1995). If the absorption of ingested Mn from milk is about 75 percent, while that from standard diets is only about 10 percent, the AI of Mn for growing puppies may be estimated at 250 $\mu g \cdot kg\ BW^{-1} \cdot d^{-1}$ (380 $\mu g \cdot kg\ BW^{-0.75} \cdot d^{-1}$). (Meyer, 1984; Henry, 1995). A diet containing 1.4 mg Mn per 1,000 kcal ME would thus provide the adequate Mn intake for a 5.5-kg puppy consuming 1,000 kcal $ME \cdot d^{-1}$.

With regard to adult dogs, from studies of the mineral requirements of pregnant bitches, Meyer (1984) estimated a maintenance Mn allowance (i.e., not including that needed for fetal deposition) of 100 μg Mn·kg $BW^{-1} \cdot d^{-1}$, which included an estimated bioavailability, including absorption efficiency, of 10 percent. Hill et al. (2001) fed adult hound dogs four similar diets differing only in source of protein. These diets contained 22.4 mg $Mn \cdot kg^{-1}$ and provided 287 μg Mn·kg $BW^{-1} \cdot d^{-1}$ (Hill et al., 2001). Apparent percentage absorption of ingested Mn was indistinguishable from zero, suggesting a very low true absorption. By comparing the two sets of data an AI of 80 μg Mn·kg $BW^{-1} \cdot d^{-1}$ (160 $\mu g \cdot kg\ BW^{-0.75} \cdot d^{-1}$) is suggested for an adult dog. A diet containing 1.20 mg Mn per 1,000 kcal would provide the AI for a 15-kg adult dog consuming 1,000 kcal $ME \cdot d^{-1}$.

Requirements and Allowances for Gestation and Lactation in Dogs

Meyer (1984) estimated the Mn allowance of the pregnant bitch to be 0.14 mg·kg $BW^{-1} \cdot d^{-1}$. This value assumed a bioavailability of 10 percent. While there are no reports of Mn allowances for lactating bitches, the data of Meyer (1984), Oftedal (1984), and Kienzle et al. (1985) may be used to derive an estimate of AI. Beagle bitches used in the studies of Oftedal (1984) had an average postpartal weight of 12.5 kg and were nursing an average of six puppies that weighed an estimated 1.2 kg each at peak lactation (approximately 4 weeks of age). At 4 weeks of age, nursing puppies have been estimated to have an intake of 50 μg·Mn·kg $BW^{-1} \cdot d^{-1}$ (Kienzle et al., 1985). Thus, the Mn needed to nurse six puppies weighing 1.2 kg each is 360 $\mu g \cdot d^{-1}$. Assuming an availability of 10 percent as suggested by Meyer (1984), this would require 3.6 mg of dietary Mn. The maintenance allowance of 80 μg Mn·kg $BW^{-1} \cdot d^{-1}$ would add another 1.0 mg for a total intake of approximately 4.6 mg $Mn \cdot d^{-1}$ or about 0.40 mg Mn·kg $BW^{-1} \cdot d^{-1}$ (0.87 mg Mn·kg $BW^{-0.75} \cdot d^{-1}$.). If this is considered as the AI, a diet containing 1.8 mg Mn per 1,000 kcal ME would provide this amount of Mn for a 22-kg bitch nursing eight puppies and consuming 5,000 kcal $ME \cdot d^{-1}$.

Safe Upper Limit of Manganese for Dogs

There are no available data that can be used to predict a SUL for Mn in dogs.

Manganese Requirements and Allowances for Cats

Because of the paucity of information, it is difficult to provide absolute recommendations for dietary Mn allowances for kittens, for adult cats, or for gestation and lactation. Scott (1960) reported feeding a purified diet containing 2.28 mg $Mn \cdot kg^{-1}$ to kittens for many months without any signs of Mn deficiency. Although no data on caloric content were provided, if this diet contained 4,000 kcal $ME \cdot kg^{-1}$, it would have provided approximately 130 μg Mn·kg $BW^{-1} \cdot d^{-1}$. Since this was a purified diet, digestibility of Mn was probably quite high. For a potentially decreased bioavailability of Mn in standard diets, as described by Henry (1995), or decreased energy intake, an adequate dietary concentration of 4.8 mg $Mn \cdot kg^{-1}$ (1.2 mg Mn per 1,000 kcal ME) is suggested. If this is the case the AI of Mn for an 800-g kitten consuming 180 kcal $ME \cdot d^{-1}$ would be 270 μg Mn·kg $BW^{-1} \cdot d^{-1}$ (250 μg Mn·kg $BW^{-0.67} \cdot d^{-1}$).

For adult cats, Scott (1964, 1975) suggested that 200 μg $Mn \cdot d^{-1}$ (approximately 3.2 $mg \cdot kg^{-1}$ diet) provided an adequate amount of this mineral, but no supporting data were included (Scott, 1964, 1975). Since data from other species suggest that this estimate may be low, a correction to 4.8 mg Mn and 4,000 kcal $ME \cdot kg^{-1}$ is suggested. Such a diet would

provide an AI of 75 μg Mn·kg $BW^{-1}·d^{-1}$ (119 μg Mn·kg $BW^{-0.67}·d^{-1}$) for a 4-kg adult cat consuming 250 kcal $ME·d^{-1}$.

With respect to gestation and lactation, the data of Keen et al. (1982) and Dobenecker et al. (1998) provide information that can be used to estimate an AI of Mn. Keen et al. (1982) reported the Mn concentration of queens' milk to be 0.3 $μg·mL^{-1}$ during the fourth week of lactation. Dobenecker et al. (1998) reported milk production as a function of weeks of lactation, BW, and litter size that would be 220 mL in a 4-kg queen nursing four kittens during the fourth week of lactation. The Mn secreted in milk would thus be 66 μg. Given 10 percent bioavailability of dietary Mn, the cat would have to consume 660 μg Mn for milk production plus 300 μg Mn for maintenance, or a total AI of 240 μg Mn·kg $BW^{-1}·d^{-1}$ (380 μg Mn·kg $BW^{-0.67}·d^{-1}$). A diet containing 1.8 Mn per 1,000 kcal ME would provide the AI of a 4-kg queen nursing four kittens and consuming 540 kcal $ME·d^{-1}$. Such a diet would also meet the AI for a 4-kg queen in late gestation.

Safe Upper Limit of Manganese for Cats

No data are available that can be used to predict a SUL for dietary Mn in kittens or adult cats.

Selenium

Selenium is a mineral that is widely distributed in animal tissues, yet is present in only very small amounts in any given organ or tissue. Although the highest concentrations of Se in most species are in liver and kidney, the organ with the greatest total amount of Se is muscle (Levander, 1986). Petfood ingredients may vary widely in their Se content. Although cereal grains contain approximately 0.3 mg $Se·kg^{-1}$ on average, this can vary widely depending on geographic source (i.e., the Se content of soils in which grains were grown). Animal tissues vary in their Se content depending on its concentration in the diets. Some fish products such as salmon and herring meals may have concentrations of Se close to 2.0 $mg·kg^{-1}$ (Levander, 1986). Because of the variability in Se content of ingredients, dog and cat foods frequently contain supplemental forms, generally as sodium selenite, 45.6 percent Se, or sodium selenate decahydrate, 21.4 percent Se (Table 13-9).

One of the major functions of Se is its role in the Se-containing enzyme glutathione peroxidase (GSH-Px), an important antioxidant that protects the body against free-radical and other oxidative damage. It is thought that GSH-Px functions as an intracytoplasmic antioxidant, whereas vitamin E plays a major role as an intramembranous antioxidant, which is one reason that deficiency diseases of these two substances are often referred to as vitamin E-Se responsive diseases (VESRDs) (Lannek and Lindberg, 1975; Levander, 1986). However, Se, in the form of selenocysteine, also functions in two deiodinases that are important in the formation and degradation of triiodothyronine, the active form of thyroid hormone (Larsen and Berry, 1995). There are several other Se-containing proteins, whose functions are not entirely clear. Selenium also plays an important role in support of the immune response (Sheffy and Schultz, 1979; Lessard et al., 1993; Bowers, 1997). Finally, there is a growing body of evidence that Se may be protective against cancer (Levander, 1986).

Absorption and Bioavailability of Dietary of Selenium in Dogs and Cats

There is very little information on the absorption or bioavailability of dietary Se specifically in dogs and cats. Using a Se-depleted chick bioassay, Wedekind et al. (1997) found that Se bioavailability from a number of petfood ingredients averaged only about 20 percent of that from sodium selenite. Plant sources of Se were more bioavailable than animal sources (Wedekind and Combs, 2000). In a subsequent study using the same model, results showed that Se bioavailability was 27 percent for animal source products, 47 percent for plant-derived ingredients, 30 percent for canned petfoods, and 53 percent for dry extruded petfoods (Wedekind et al., 1998).

At the end of an 8-week repletion study in a Se-depleted rat model, a number of different meat sources, bread, and seafood were reported to be good sources of bioavailable Se, resulting in an increase in GSH-Px activity to levels as high as or higher than those in control animals (Wen et al., 1995). In the rat, Se has been reported to be efficiently absorbed from the intestine, mainly the duodenum. Both inorganic sources such as sodium selenite and organic sources such as selenomethionine and selenocystine are over 90 percent absorbed (Levander, 1986). However, the results of these studies may not be applicable to Se from mixed diets. Windisch et al. (1998) reported apparent absorption of ingested Se, as sodium selenate, in rats to be 82 percent, while that from selenocysteine and selenomethionine was 90 percent or higher. However, they concluded that the organic forms of Se were mainly incorporated into protein (in amino acids) and not available for metabolic functions of Se.

The Se bioavailability reported from the experiments of Wedekind et al. (1997, 1998) using the chick model are somewhat lower than those of Wen et al. (1995) using the rat model with respect to Se availability from animal sources. The reasons for this are not clear. Reasbeck et al. (1985) found that organic forms of Se were more rapidly absorbed in the jejunum of dogs, probably through the active transport of Se-containing amino acids, whereas sodium selenite appeared to be absorbed by diffusion, although total absorption of Se was not evaluated in these studies.

The results of these studies suggest that many forms of Se are bioavailable in dogs and cats. There appears to be little homeostatic control of Se absorption, the absorption per-

centage being high regardless of the dietary concentration of this mineral. The bioavailability of Se from different sources may differ for different physiologic purposes (Levander, 1986; Wedekind and Combs, 2000). There is a dearth of information on interaction of Se with other minerals at the level of intestinal absorption. However, Houpt et al. (1988) suggested that dietary Se may be protective, perhaps through a competitive effect on absorption, against the effects of mercury toxicity in cats.

Selenium Deficiency in Dogs and Cats

Only one paper reports experimentally produced clinical signs of Se deficiency in dogs; there are no reports for cats. VanVleet (1975) observed clinical signs of vitamin E-Se responsive disease when puppies were fed a basal Se and vitamin E-deficient diet (0.01 mg $Se \cdot kg^{-1}$). Clinical signs appearing within 6 to 8 weeks included anorexia, depression, dyspnea, and coma. At necropsy, ventral edema, generalized skeletal muscular pallor and edema with scattered white streaking, brownish-yellow discoloration of intestinal muscle, and a chalky white deposit at the renal corticomedullary junction were noted. Histopathologic changes included muscular degeneration, focal subendocardial necrosis in the cardiac ventricular musculature, intestinal liopfuscinosis, and renal mineralization (Van Vleet, 1975). Puppies fed the basal diet supplemented with 0.5 mg $Se \cdot kg^{-1}$ demonstrated mild skeletal muscle myopathy.

Using serum Se data, Wedekind and Combs (2000) found that purified diets with less than 0.21 mg $Se \cdot kg^{-1}$ fed to 9-week-old beagle puppies did not support normal serum Se concentrations. Because of the role of Se in deiodinases, the effects of these diets on thyroid hormone concentrations were also measured, with the results suggesting that Se deficiency may not be a major factor in the development of canine hypothyroidism (Wedekind et al., 2001). In 10-week-old kittens, breakpoint analysis of serum GSH-Px concentration indicated that diets containing less than 0.12 mg $Se \cdot kg^{-1}$ were inadequate to maintain normal circulating concentrations of this enzyme (Wedekind and Combs, 2000; Wedekind et al., 2000). Other parameters measured demonstrated breakpoints at lower concentrations, emphasizing differing needs of Se for different physiological functions (Wedekind and Combs Jr., 2000; Wedekind et al., 2000). Yu et al. (2001) evaluated the effect of a low-Se diet (0.02 $mg \cdot kg^{-1}$) on thyroid function in kittens. Compared to kittens fed a diet containing 0.4 mg $Se \cdot kg^{-1}$ as sodium selenate, kittens fed the Se-deficient diet demonstrated reduced plasma Se concentration and GSH-Px activity, although no gross clinical signs of Se deficiency were observed. Plasma concentration of thyroxine increased, while that of 3,5,3′-triiodothyronine decreased significantly in kittens fed the Se-deficient diet. However, the concentration of thyroxine did not exceed the normal range nor did the concentration of 3,5,3′-triiodothyronine fall below the normal range in either group (Yu et al., 2001). The results suggested that Se does play a role in thyroid hormone metabolism but agree with previous data suggesting that Se status may not play a major role in the development of hypothyroidism in cats (Wedekind et al., 2001). However, this experiment lasted only 8 weeks, so more work in this area is needed.

Adverse Effects of Excess Consumption of Selenium in Dogs and Cats

There is little evidence regarding adverse effects of excess consumption of dietary Se by dogs and cats. Summarizing older studies, Levander (1988) reported that excess consumption of Se by dogs (e.g., diets containing 5.0 $mg \cdot kg^{-1}$ diet) resulted in a microcytic, hypochromic anemia, progressing in severity with time, and severe liver damage including necrosis and cirrhosis.

Dietary Selenium Requirements and Allowances for Dogs

Requirements and Allowances for Puppies and Dogs

In a study of experimentally induced vitamin E and Se deficiency in puppies, the data of VanVleet (1975) suggest that feeding diets containing at least 0.5 mg $Se \cdot kg^{-1}$ prevented clinical signs of selenium deficiency. However, the diet used was vitamin E-deficient, which may have increased the Se requirement. Using breakpoint analysis of serum Se concentrations, a minimum dietary requirement for beagle puppies of 0.21 mg $Se \cdot kg^{-1}$ diet has been determined (Wedekind and Combs, 2000). Using a chick bioassay system, a bioavailability factor of 30 percent was suggested for Se in standard diets, and a RA of 0.5 mg $Se \cdot kg^{-1}$ diet was suggested (Wedekind et al., 1998).

No information on caloric content of the diets was provided in the above studies. If, however, it was reasonably close to 4,000 kcal $ME \cdot kg^{-1}$, the MR of dietary Se for puppies would be 52.5 µg per 1,000 kcal ME, which would provide 9.5 µg $Se \cdot kg\ BW^{-1} \cdot d^{-1}$ (13.7 µg $\cdot kg\ BW^{-0.75} \cdot d^{-1}$) to a 5.5-kg puppy consuming 1,000 kcal $ME \cdot d^{-1}$. From bioavailability studies of Se in petfoods, Wedekind and Combs (2000) suggested 0.5 mg $Se \cdot kg^{-1}$, DM basis, as the RA for puppies. However, since many petfoods are now supplemented with inorganic Se salts, which are more highly bioavailable, a recommended dietary concentration of 0.35 mg Se per 4,000 kcal $ME \cdot kg^{-1}$ is more reasonable, agreeing reasonably well with the data of VanVleet (1975) assuming diets with adequate vitamin E. Such a diet would contain 87.5 µg Se per 1,000 kcal ME and would provide 16.5 µg $Se \cdot kg\ BW^{-1} \cdot d^{-1}$ (25.1 µg $\cdot kg\ BW^{-0.75} \cdot d^{-1}$) to a 5.5-kg puppy consuming 1,000 kcal $ME \cdot d^{-1}$.

There are no data on the Se needs of adult dogs. Therefore, it may be assumed that a diet containing sufficient Se to support the growth of puppies (i.e., the RA of 0.35 mg $Se \cdot kg^{-1}$ and 4,000 kcal $ME \cdot kg^{-1}$), represents an AI for the

adult dog. A 15-kg adult dog consuming 1,000 kcal ME·d^{-1} would thus have an AI of 6 µg Se·kg BW^{-1}·d^{-1} (11.8 µg·kg $BW^{-0.75}$·d^{-1}).

Requirements and Allowances for Gestation and Lactation in Dogs

There are no data available regarding Se requirements and allowances for gestation or lactation in the dog. It can only be assumed, as stated above, that dietary concentrations sufficient to support the RA for growth (i.e., 0.35 mg Se·kg^{-1} and 4,000 kcal ME·kg^{-1}) would provide an AI for reproduction as well. Assuming this to be the case, a 22-kg bitch in late gestation or nursing eight puppies and consuming 5,000 kcal ME·d^{-1} would have an AI of 20 µg Se·kg BW^{-1}·d^{-1} (43 µg·kg $BW^{-0.75}$·d^{-1}).

Safe Upper Limit of Selenium for Dogs

While Levander (1986) reported that a dietary Se concentration of 5 mg·kg^{-1} resulted in Se toxicity in dogs, no data are available on an acceptable SUL for dietary Se in dogs although for regulatory purposes, a maximum standard of 2.0 mg Se·kg^{-1} has been suggested (AAFCO, 2001).

Dietary Selenium Requirements and Allowances for Cats

Requirements and Allowances for Kittens and Adult Cats

Using breakpoint analysis for several variables, the highest Se requirement, for serum GSH-Px activity, occurred at an estimated 0.12 mg Se·kg^{-1} diet fed to 10-week-old kittens, which can therefore be considered the minimal Se requirement for kittens (Wedekind and Combs, 2000; Wedekind et al., 2000). Based on Se bioavailability studies in cat foods using the chick model, Wedekind et al. (1998) extrapolated a bioavailability factor of 0.3 that may be applied to arrive at a recommended dietary allowance of 0.4 mg Se·kg^{-1} (Wedekind et al., 1998, 2000; Wedekind and Combs, 2000). However, it is likely that bioavailability of Se in cat foods, especially those supplemented with inorganic Se salts, may be somewhat higher than measured in the above studies, so a recommended dietary allowance of 0.3 mg Se·kg^{-1} is suggested.

No data on dietary caloric content were provided in these studies. However, if caloric density is assumed to be close to 4,000 kcal ME·kg^{-1}, the MR and daily RA, respectively, of dietary Se in growth foods for kittens can be estimated at 0.03 mg and 0.075 mg Se per 1,000 kcal ME. An 800-g kitten consuming 180 kcal ME·d^{-1} would thus have a MR and a RA of 6.75 µg and 17 µg Se·kg BW^{-1}·d^{-1} (6.23 and 15.8 µg·kg $BW^{-0.67}$·d^{-1}), respectively.

There are no reports of the Se requirement of adult cats. Therefore, it may be assumed that diets with Se concentrations adequate to support growth (i.e., 0.3 mg Se·kg^{-1} and 4,000 kcal ME·kg^{-1}) will provide an AI for adult cats as well. The AI of a 4-kg adult cat consuming 250 kcal ME·d^{-1} would therefore be estimated at 4.7 µg Se·kg BW^{-1}·d^{-1} (6.95 µg·kg $BW^{-0.67}$·d^{-1}).

Requirements for Gestation and Lactation in Cats

There are no data on which to base a MR or RA of Se in pregnant or nursing queens. Therefore, a dietary concentration of Se that is adequate for growth (i.e., 0.3 mg Se·kg^{-1} and 4,000 kcal ME·kg^{-1}) is assumed to be adequate for reproduction, as well. A 4-kg queen nursing four kittens and consuming 540 kcal ME·d^{-1} would accordingly have an AI of 10 µg Se·kg BW^{-1}·d^{-1} (16 µg·kg $BW^{-0.67}$·d^{-1}).

Safe Upper Limit of Selenium for Cats

There are no data available that can be used to predict a SUL of dietary Se for cats.

Iodine

Iodine is an essential nutritional element that is required by animals in only very small amounts. Its biological significance is that it is a major constituent of the thyroid hormones thyroxine (T_4) and 3,5,3′-triiodothyronine (T_3), the latter being considered the active form of the hormone. Thyroid hormone plays a major role in cell differentiation, growth, and development in growing animals and in the regulation of metabolic rate in adults. The bodies of healthy dogs and cats contain only a few milligrams of I, the vast majority of which is located in a protein-bound form in the thyroid gland, although much smaller amounts occur in other organ systems. Iodine circulates in the blood in both inorganic and organic forms, with blood inorganic I concentration being related to the I status of the animal (Hetzel and Maberly, 1986).

The amount of I in foodstuffs varies widely. Meat, for example, contains very low concentrations while seafood is generally very high in I (Scott et al., 1961; Hetzel and Maberly, 1986). Iodine content of foodstuffs also varies due to natural differences in environmental I, with foodstuffs from geographic areas close to salt water having higher I content than those from inland sources. Iodine supplements are frequently added to petfoods in the form of inorganic I, the most common supplements being potassium iodide, 68.2 percent I; cuprous iodide, 67 percent I; calcium iodate, 65.1 percent I; and calcium periodate, 28-31 percent I (Table 13-8). Nonetheless, the I content of petfoods can apparently vary considerably (Johnson et al., 1992; Losher et al., 2000; Castillo et al., 2001a).

Absorption and Bioavailability of Dietary Iodine in Dogs and Cats

Iodine exists in food ingredients and water mainly in the inorganic form, and it is generally quantitatively absorbed

from all levels of the gastrointestinal tract. A small amount of organically bound I also may be ingested, mainly in the form of iodinated amino acids, and a small amount of I in this form may appear in the feces. The major source of I excretion is the kidney. Inorganic I is filtered in the glomerulus, and there is no tubular mechanism for conservation (Hetzel and Maberly, 1986). There is little evidence to suggest significant interference of other minerals with the absorption of I, but high concentrations of dietary Ca and K have been suggested as possibilities (Gross et al., 2000).

Iodine Deficiency in Dogs and Cats

There are a few reports of clinical cases of I deficiency in mature dogs (Thompson, 1979; Nuttall, 1986). In all cases, the diagnosis was based on a history of the dogs being fed an all-meat diet and responding to I treatment. Clinical signs consisted of goiter (enlargement of the thyroid gland), alopecia, dry sparse overall hair coat, and weight gain. Reduced concentrations of circulating thyroid hormones were measured in some, but not all, of these cases.

Norris et al. (1970) evaluated the response to long-term feeding (more than 1 year) of a diet containing an estimated 80 μg I per 1,000 kcal equivalent to a diet containing 0.3 mg $I \cdot kg^{-1}$ and 4,000 kcal $ME \cdot kg^{-1}$ and providing about 5.2 μg $I \cdot kg\ BW^{-1} \cdot d^{-1}$. During the first 9 months the thyroid glands became hyperplastic and hypertrophic indicating a state of I deficiency. This was accompanied by significant increases in thyroid uptake of test doses of ^{131}I and rapid loss of the radiolabel after the time of maximum uptake (Norris et al., 1970). However, during succeeding months, the thyroid glands decreased in size and returned to a normal histological appearance despite continued increased uptake of radiolabeled I. These results suggest that dogs can adapt over time to significant reductions in I intake. In a 5-month study, dogs with daily I intakes of ≤ 7.5 μg $I \cdot kg\ BW^{-1} \cdot d^{-1}$ (≤ 112 μg I per 1,000 kcal ME) demonstrated significant changes in several parameters of I metabolism and thyroid function, suggesting that these intake levels were insufficient to maintain normalcy, although no clinical signs of I deficiency occurred (Belshaw et al., 1975).

There is very little information available on I deficiency in cats. Scott et al. (1961) fed 10- to 14-week-old kittens diets of raw beef or sheep heart for 8 weeks or more. The I concentration of the diet averaged 0.45 $mg \cdot kg^{-1}$, DM basis, which provided 5-40 μg $I \cdot d^{-1}$ to each kitten. Other kittens were fed a stock diet providing 200-300 μg $I \cdot d^{-1}$. Although no clinical signs directly attributable to I deficiency were described, on autopsy the thyroid glands from the kittens fed the raw heart diet were enlarged and demonstrated histological changes compatible with I deficiency. Kittens fed raw heart supplemented with 100 μg $I \cdot d^{-1}$ remained normal, but supplements of 50 μg $I \cdot d^{-1}$ (equivalent to a diet containing about 1.1 mg $I \cdot kg^{-1}$ and 4,000 kcal $ME \cdot kg^{-1}$) did not prevent some signs of thyroid gland hyperplasia. More recently, Smith (1996) reported that feeding adult cats diets with concentrations of less than 2.4 I $mg \cdot kg^{-1}$ resulted in metabolic changes compatible with I deficiency although no clinical abnormalities were observed (Smith, 1996; Gross et al. 2000).

Ranz et al. (2002) investigated a potential role of I deficiency as an etiological factor in feline hyperthyroidism by comparing the I content of cat foods and the incidence of thyroid disease in cats in Germany. Although the results were inconclusive, a possible relationship between reduced I intake and thyroid disease was suggested (Ranz et al., 2002). Reduced I intake has also been reported to result in increased clinical incidence of thyroid disease and thyroid tumors in dogs in I-deficient areas of Germany (Prange, 2001a,b).

Adverse Effects of Excess Consumption of Iodine in Dogs and Cats

Excessive I intake can lead to significant abnormalities in many domestic animal species. Clinical signs may include excessive lacrimation, salivation, nasal discharge, and a flaky and dry skin and hair coat. Goiter can occur in foals of mares that have ingested excessive amounts of I. This appears to be due to a negative effect of high plasma concentrations of I on production of thyroid hormones (Radostits et al., 2000). High concentrations of dietary I, up to 14 $mg \cdot kg^{-1}$, in cat food have been shown to result in transient decreases in thyroid hormone levels (Tarttelin et al., 1992; Kyle et al., 1994; Tarttelin and Ford, 1994).

A similar response to increased dietary I (5.6 $mg \cdot kg^{-1}$, DM basis) has been reported in puppies. This amount of dietary I was also shown to decrease uptake of radioiodine by the thyroid gland (Castillo et al., 2001a). More recently, Castillo et al. (2001b) reported findings of bone abnormalities in puppies fed diets containing high concentrations of I, which resulted in I intakes of up to 775 $\mu g \cdot kg\ BW^{-1} \cdot d^{-1}$. While excessive dietary I in cat food has been investigated as a potential cause of feline hyperthyroidism, epidemiologic studies have not identified a relationship between dietary I and functional adenomas or adenocarcinomas of the thyroid gland in the cat (Scarlett, 1994).

Dietary Iodine Requirements and Allowances for Dogs

Requirements and Allowances for Puppies and Adult Dogs

There are no reports of I requirements of growing puppies. Norris et al. (1970) fed 11-month-old beagle dogs' diets containing 50-75 μg $I \cdot d^{-1}$. Provided these dogs were close to mature weight and consumed normal amounts of energy, they would have an intake of approximately 5 μg $I \cdot kg\ BW^{-1} \cdot d^{-1}$, which would be equivalent to a dietary concentration of 75 μg I per 1,000 kcal ME (Norris et al., 1970). The dogs in this study did not develop clinical signs of I deficiency, but they did show metabolic and histological alterations of the thyroid glands compatible with hypothyroidism

during the first 9 months of feeding the test diet. By the end of 1 year on the diet however, thyroid gland histology had returned to normal and most of the metabolic changes had normalized, suggesting adaptation to this level of I intake (Norris et al., 1970). Belshaw et al. (1975) found that intakes of 140 μg $I \cdot d^{-1}$ or higher in adult beagles, corresponding to 175 μg I per 1,000 kcal ME and a consumption of 12 μg I·kg $BW^{-1} \cdot d^{-1}$ (23.6 μg·kg $BW^{-0.75} \cdot d^{-1}$) were required to maintain normalcy in all metabolic, kinetic, and histological parameters evaluated.

To correct for variation in energy intake and goitrogenic substances in the diet, an allowance of 25 percent is recommended. Thus, the RA of dietary I for adult dogs may be set at 220 μg I per 1,000 kcal. The recommended daily allowance of I for a 15-kg dog consuming 1,000 kcal ME would be 15 μg·kg $BW^{-1} \cdot d^{-1}$ (29.6 μg·kg $BW^{-0.75} \cdot d^{-1}$). Assuming that this concentration of I in food also supports growth, a 5.5-kg puppy consuming 1,000 kcal $ME \cdot d^{-1}$ would have an AI of 40 μg I·kg $BW^{-1} \cdot d^{-1}$ (61.0 μg·kg $BW^{-0.75} \cdot d^{-1}$).

Requirements and Allowances for Gestation and Lactation in Dogs

There are no available data on I requirements for reproduction in the dog. However, based on the data of Norris et al. (1970) and Belshaw et al. (1975) suggesting that adult dogs can adapt to reasonably low intakes of dietary I, it is likely that the recommended dietary concentration of I for adult dogs may support the needs of reproduction as well. If this is the case, the AI for a 22-kg bitch in late gestation or nursing eight puppies and consuming 5,000 kcal $ME \cdot d^{-1}$ is 50 μg I·kg $BW^{-1} \cdot d^{-1}$ (108 μg·kg $BW^{-0.75} \cdot d^{-1}$).

Safe Upper Limit of Iodine for Dogs

In the course of their studies, Belshaw et al. (1975) measured I concentrations in several commercial brands of dog food. The results corresponded to concentrations ranging, at a minimum, from 400 to 1,275 μg I per 1,000 kcal ME, providing estimated daily intakes of 27-85 μg I·kg $BW^{-1} \cdot d^{-1}$ in adult dogs (Belshaw et al., 1975). Apparently these foods were fed without any clinical abnormalities in dogs consuming them. On the other hand, Castillo et al. (2001a) reported evidence of depressed thyroid gland function, evidenced by reduced plasma concentrations of thyroid hormones and bone abnormalities, in puppies fed diets containing an estimated maximum I content of 1,400 μg I per 1,000 kcal ME, providing an estimated 250 μg I·kg $BW^{-1} \cdot d^{-1}$. Based on this information an absolute figure for a SUL of dietary I cannot be predicted for adult dogs.

Dietary Iodine Requirements and Allowances for Cats

Requirements and Allowances for Kittens and Adult Cats

There are very few data available on which to base a recommendation for I requirements and allowances in cats. Scott et al. (1961) produced I deficiency in kittens by feeding a raw beef heart diet containing approximately 0.4 mg $I \cdot kg^{-1}$ for a period of 8 weeks beginning at 12 weeks of age. The diet contained a reported 4,400 kcal $ME \cdot kg^{-1}$, and at the end of 8 weeks the kittens were consuming an estimated 140 kcal ME·kg $BW^{-1} \cdot d^{-1}$, providing about 12.7 μg I·kg $BW^{-1} \cdot d^{-1}$. Subsequent supplementation with 100 μg $I \cdot d^{-1}$ for an additional 6 weeks, providing conservative estimated daily intakes of 45 μg I·kg $BW^{-1} \cdot d^{-1}$, reversed all signs of I deficiency in these kittens. The kittens were about 26 weeks of age at the end of the experiment and weighed an estimated 2.5 kg (Loveridge, 1987). At this age, the kittens were consuming an estimated 110 kcal·kg $BW^{-1} \cdot d^{-1}$, which resulted in an I intake equivalent to that from a diet containing 410 μg I per 1,000 kcal.

Adding an allowance of 10 percent to account for variations in energy intake and possible reduced availability of I in standard diets, the adequate dietary I concentration would be 450 μg per 1,000 kcal ME. This diet would provide an I intake of 100 μg·kg $BW^{-1} \cdot d^{-1}$ (93 μg·kg $BW^{-0.67} \cdot d^{-1}$) to an 800-g kitten consuming 180 kcal $ME \cdot d^{-1}$.

An adult 4-kg cat consuming 250 kcal $ME \cdot d^{-1}$ of an equivalent diet would have an AI of 28 μg I·kg $BW^{-1} \cdot d^{-1}$. Recent preliminary information reported by Smith (1996) indicates that diets with concentrations of less than 2.4 mg $I \cdot kg^{-1}$ fed to adult cats may result in metabolic alterations compatible with I deficiency or suboptimal I intake. This implies that the suggested AI of I for adult cats is reasonable (Smith, 1996).

However, Ranz et al. (2002) concluded from feeding trials of various concentrations of dietary I to adult cats that bioavailability of dietary I approximates 100 percent, that fecal endogenous I loss was a constant 13 μg I·kg $BW^{-1} \cdot d^{-1}$ regardless of I intake, and renal endogenous loss was 6 μg I·kg $BW^{-1} \cdot d^{-1}$ at zero I intake for a total mandatory endogenous loss of 20 μg I·kg $BW^{-1} \cdot d^{-1}$ (31.6 μg·kg $BW^{-0.67} \cdot d^{-1}$). They concluded that an intake of this amount of dietary I should be suffiecient to maintain zero I balance in the adult cat. A diet containing 320 μg I per 1,000 kcal ME would thus provide the dietary MR of iodine for a 4 kg adult cat assuming a caloric intake of 250 kcal $ME \cdot d^{-1}$. To correct for possible variations in energy intake or the unlikely possibility of reduced bioavailability, a safety factor of 10 percent can reasonably be applied, suggesting a dietary RA of 350 μg I per 1,000 kcal ME for adult maintenance.

Requirements and Allowances for Gestation and Lactation in Cats

There is no information available on I requirements or allowances for reproduction in cats. By assuming that a diet, adequate for growth, would supply the needs for reproduction as well, a 4-kg cat in late gestation or nursing four kittens and consuming 540 kcal $ME \cdot d^{-1}$ would have an AI of 61 μg I·kg $BW^{-1} \cdot d^{-1}$ (96 μg·kg $BW^{-0.67} \cdot d^{-1}$).

Safe Upper Limit of Iodine for Cats

Kyle et al. (1994) evaluated thyroid function in cats fed a diet containing 21.1 mg I·kg^{-1}, DM basis, for 5 months. No clinical abnormalities were reported. Further, free thyroxine concentrations remained in the normal range throughout the study (based on monthly sampling), suggesting that consumption of a diet with this I concentration had no negative effects on thyroid function at least during the time frame studied. However, Tarttelin and Ford (1994) did report significant depression in serum free thyroxine concentrations when a diet containing 13.8 mg I·kg^{-1} DM basis was fed for a period of only two weeks. Based on the results of these experiments, it is not possible to define a safe upper limit for iodine consumption in cats.

OTHER MINERALS

Arsenic

Although arsenic (As) is often thought of as toxic, it appears that only certain As-containing compounds (e.g., trimethylarsenic) are highly toxic, while organic arsenical compounds, such as those found in crustacean seafood, are quite safe when ingested (Anke, 1986). From studies in chickens, hamsters, goats, miniature pigs, and rats, it appears that As is an essential nutrient for these species, though it is required in amounts of only a few hundred nanograms per gram of diet (Anke, 1986; Nielsen, 1994b).

Arsenic deficiency in these species has been associated with clinical signs of reduced growth rate, impaired fertility, and increased perinatal mortality. At the microscopic level, myocardial damage has been noted in As-deficient goats, most specifically at the level of the mitochondrion where membrane damage and rupture have been described (Nielsen, 1994b). Anke (1986), summarizing several studies, indicated that As deficiency is also associated with abnormal function of several enzyme systems that may be involved in amino acid metabolism and protein synthesis.

There is insufficient information to make any recommendations regarding As allowances for dogs or cats. Research in this area would be useful.

Boron

There is an increasing body of evidence suggesting that B is an essential nutrient for both humans and animals (Nielsen, 1986, 1994b). Boron deprivation depresses growth and causes increased plasma alkaline phosphatase concentrations in vitamin D-deficient chicks. Studies in rats suggest that B influences parathormone activity and, indirectly, the metabolism of Ca, P, Mg, and vitamin D and, therefore, is of importance in Ca homeostasis and bone metabolism. Boron also has an effect on brain electrical activity, perhaps secondary to its effects on Ca and Mg metabolism (Nielsen 1986, 1994b).

Data from rats and chicks demonstrate that feeding diets containing 0.3 mg B·kg^{-1} may result in signs of altered Ca and Mg metabolism (Nielsen 1986). Thus, higher dietary levels may be indicated. Data from human studies suggest the possibility of a B requirement of 0.5 mg B per 1,000 kcal (Nielsen, 1994b).

There is insufficient information to make any recommendations regarding B allowances for dogs or cats. Research in this area would be useful.

Chromium

Chromium has been recognized as an essential nutrient for about 50 years, since studies in rats identified it as being essential for normal glucose tolerance (Anderson, 1987; Nielsen 1994a). Subsequently, signs of Cr deficiency in humans and several animal species have been found to include impaired glucose tolerance, elevated plasma insulin, hyperglycemia, impaired growth, elevated plasma triglycerides, neuropathy, encephalopathy, corneal lesions, and decreased fertility and sperm count (Anderson, 1987). Chromium has also been shown to be involved in lipid metabolism, protein synthesis, and nucleic acid metabolism.

There are few data on Cr intakes in species other than humans. For technical reasons, only recent estimates are assumed to be valid (Nielsen, 1994a). Even recent estimates vary widely depending on many factors, but it would appear that a Cr intake of 40-50 μg·d^{-1} is average for the adult human. Requirements may increase with stress such as intense physical exercise.

Little is known about Cr absorption, although it appears to be absorbed mainly in the jejunum. The chemical form of Cr may affect bioavailability. However, data on the bioavailability of Cr from inorganic sources such as chloride or various organic sources such as nicotinate or picolinate are inconsistent (Spears et al., 1998b). In several studies in both animals and humans, apparent Cr absorption of between 0.4 and 3 percent have been reported (Anderson, 1987).

A few studies have been published regarding the effect of supplemental Cr, generally in the form of chromium tripicolinate, on aspects of glucose metabolism, insulin sensitivity, reproduction and growth, and immune responsiveness in dogs (Spears et al., 1998a,b; Lindemann et al., 2000). Gestation and lactation in bitches, as well as growth of puppies, were little affected by Cr supplementation at a concentration of 0.2 mg·kg^{-1} diet. The Cr concentration of the basal diet was not reported (Lindemann et al., 2000). A small but significant decrease in blood glucose concentration was observed in dogs supplemented with Cr at a concentration of 0.3 mg·kg^{-1} diet; however, no differences in immune function were noted between dogs supplemented with 0.15 or 0.3 mg Cr·kg^{-1} diet compared to unsupplemented dogs (Spears et al., 1998a). In this study, the Cr content of the control diet was stated as approximately 0.7 mg·kg^{-1}. Schachter et al. (2001) concluded that, while Cr supplemen-

tation of diabetic dogs at the level of 2.5-7.5 μg Cr·kg $BW^{-1}·d^{-1}$ for several months was safe, there was no effect of the additional Cr on glycemic control. Cohn et al. (1999) reported that, although supplementation with 100 μg·Cr·d^{-1} was safe, the added Cr had no effect on glucose tolerance in either obese or normal cats. The Cr concentration in the basal diet was not reported.

If the basal diet used by Spears et al. (1999a) contained 4,000 kcal ME·kg^{-1} (175 μg Cr per 1,000 kcal ME), a 15-kg adult dog consuming 1,000 kcal ME·d^{-1} of this diet would have an intake of 12 μg Cr·kg $BW^{-1}·d^{-1}$. Nielsen (1994a) summarized the results of several studies and suggested that the Cr intake of adult humans may be 50-200 μg·d^{-1}. The 70-kg standard human would thus be consuming between 0.7 and 3.0 μg Cr·kg $BW^{-1}·d^{-1}$. It is likely that dogs have a Cr requirement lower than 12 μg·kg $BW^{-1}·d^{-1}$, and until further information is available, no definite recommendation can be made.

There is insufficient information to make any recommendations regarding Cr allowances for cats. Research in this area would be useful.

Molybdenum

Although an elevated dietary intake of Mo is often considered a potential contributor to Cu deficiency in ruminants, it has been shown to be an essential nutrient for humans and several animal species (Mills and Davis, 1987; Nielsen, 1994b). There are several Mo-containing metalloenzymes including xanthine oxidase, which is critical for normal nucleic acid metabolism (i.e., conversion of purines and similar compounds to uric acid). Molybdenum is also present in a few other enzymes including aldehyde oxidase and sulfite oxidase (Mills and Davis, 1987).

Numerous effects of Mo deficiency have been described in poultry, including decreased viability and hatchability of eggs and feathering defects. In goats, diets providing less than 60 μg Mo·kg $BW^{-1}·d^{-1}$ resulted in decreased rates of conception and increased rates of abortions, as well as poor growth and increased mortality rate of kids (Mills and Davis, 1987). While a deficiency has not been described in dogs and cats, it is virtually certain that Mo is an essential nutrient for these species.

Molybdenum is present in many ingredients used in petfoods including soybean meal, which may contain up to 10 mg·kg^{-1}, and cereal grains in which the concentration is only 0.2-0.4 mg·kg^{-1}. Most meat products are very low in Mo, but organ meats such as liver may contain from 2 to 10 mg·kg^{-1} (Mills and Davis, 1987). Molybdenum appears to be highly absorbable in both organic and inorganic forms. While few competitors of Mo absorption have been reported, one major exception is sulfate, which—particularly in simple-stomached animals where it is not converted to sulfide—is a potent inhibitor of Mo absorption, perhaps competing for a common carrier at the site of absorption.

Since a deficiency of Mo has not been reported in dogs or cats, it is almost certain that commercial petfoods contain sufficient Mo to meet their metabolic needs. It is quite likely that the need is significantly less than the 60 μg·kg $BW^{-1}·d^{-1}$ reported to be insufficient for the goat, a ruminant, since estimates of normal intakes for adult humans range from 40 to 460 μg Mo·d^{-1}, which represents about 1-7 μg Mo·kg $BW^{-1}·d^{-1}$ (Mills and Davis, 1987).

There is insufficient information to make any recommendations regarding Mo allowances for dogs and cats. Research in this area would be useful.

Silicon

Silicon (Si) is a ubiquitous element in the environment and was found in animal tissues from the beginnings of the science of nutrition. That it is absorbed and excreted by dogs is proven by the occurrence of Si-containing urinary calculi in this species (Ehrhart and McCullagh 1973; Aldrich et al., 1997). The first reports of Si as an essential nutrient were published in the mid-1970s from studies in chickens and rats (Nielsen, 1994b). It is now clear from studies in experimental animals that Si is an essential nutrient that plays a role in the calcification and maturation of bone. It helps enhance the early calcification of bone, since the concentration of Si is highest in young forming bones and decreases thereafter. Silicon also appears to be a cofactor in prolyl hydrase activity, which is involved in collagen synthesis (Carlisle, 1986). Signs of Si deficiency are related mainly to aberrant development of connective tissue and bone.

With respect to dietary sources, Si is found in highest concentration in plant source food ingredients and is lowest in animal source ingredients (Nielsen, 1994b). The MR of Si has not been determined with certainty for any species. It has been suggested that the Si requirement for humans may be around 30 mg·d^{-1}, or approximately 400 μg·kg $BW^{-1}·d^{-1}$, but the evidence is not conclusive.

There is insufficient information to make any recommendations regarding Si allowances for dogs and cats. Research in this area would be useful.

Nickel

The trace element nickel (Ni) was first mentioned as a nutritionally essential element in the 1930s, but most of the knowledge of its nutritional and physiological role has been obtained since the beginning of the last quarter of the twentieth century when appropriate methods for such study became available (Nielsen, 1987a,b). Summarizing studies in rats and goats, Nielsen (1994b) reported signs of Ni deficiency including poor growth and reproductive performance, reduced serum glucose concentration, and altered distribution of other mineral elements including Ca, Fe, and Zn.

There has been no description of a specific biochemical function for Ni in animals, including humans. However, because of the discovery of several Ni-containing enzymes (e.g., jack bean urease) in plants and microorganisms, Ni may play a role in metalloenzymes in higher organisms as well.

Studies in animals suggest that very little dietary Ni is absorbed from the intestine; more than 90 percent of ingested Ni appears in the feces and most absorbed Ni is excreted in the urine. Additionally, in those monogastric animals studied, the Ni requirement is quite low, probably less than 200 $\mu g \cdot kg^{-1}$ diet (Nielsen, 1994b).

Regardless of its nutritional essentiality, there is ample evidence of the toxic effects of significant Ni ingestion (Nielsen, 1987a). Toxicity of ingested Ni is generally reflected by signs of gastrointestinal irritation. However, in piglets, Ni toxicity has been reported to result in depressed growth and coarse, shaggy hair coats in addition to gastrointestinal disturbances such as diarrhea and melena.

There is insufficient information to make any recommendations regarding Ni allowances for dogs and cats. Research in this area would be useful.

Vanadium

Numerous vanadium (V) deprivation and other studies have been published suggesting the possibility of an essential nutritional role. However, as of yet no signs of V deficiency have been consistently reproducible (Nielsen, 1987b). In a large number of V deprivation studies in chicks and rats (Nielsen, 1987b), numerous abnormalities were observed but there was no variable that was consistently affected.

Suggested roles for V have included Na pump regulation, regulation of phosphoryl transferase enzymes, adenylate cyclase regulation, a regulatory role in reduced nicotinamide-adenine dinucleotide (NADH) oxidation, a role in glucose metabolism by altering or mimicking insulin activity, and a possible role in Ca metabolism at the intracellular level as well as in calcification of bone and teeth. However, an essential role for this mineral has not been proven (Nielsen, 1994b).

If there is a requirement for V it is undoubtedly very low since the V content of most foods is very low; fruits and vegetables contain less than 1-5 $ng \cdot g^{-1}$ and seafood, meats, and dairy products contain 5-30 $ng \cdot g^{-1}$. Some herbal seeds, however, may contain much higher concentrations of V.

Although no essential metabolic function has been identified, V toxicity has been described (Nielsen, 1987b). Dietary V concentrations of 25 $\mu g \cdot g^{-1}$ have been shown to cause depressed growth in chicks, and concentrations of more than twice that amount resulted in mortality. However, other dietary constituents can affect the toxicity of V.

There is insufficient information to make any recommendations regarding V allowances for dogs and cats. Research in this area would be useful.

Miscellaneous Minerals

While there are a number of other minerals present in the environment and some have been suggested to be essential in other species, there is no reproducible evidence that any of them are essential for metabolic functions in dogs and cats (Mertz, 1986; Nielsen, 1986, 1994b). However, it is possible, indeed likely, that future research will result in additional mineral elements being identified as essential nutrients for these two species.

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8

Vitamins

INTRODUCTION

Vitamins are organic compounds, essential at low concentrations in the diet, that are required to sustain metabolic functions: Either they are not synthesized from precursors in the diet, or, under certain conditions, their rate of synthesis is suboptimal. Vitamins participate in a wide range of metabolic functions, and neither the names of the vitamins nor the numerical subscripts give insights into their functional roles. Dietary vitamin deficiencies produce a range of clinical abnormalities that reflect the diverse metabolic functions of vitamins. When the diet is inadequate in a vitamin, the tissues are frequently depleted at variable rates and have different sensitivities to the deficiency. This produces a progression of clinical signs, depending on the severity of the deficiency, and many vitamin deficiencies follow a defined chronology.

Alleviation of clinical signs of deficiency following supplementation with the isolated vitamin provides strong presumptive evidence that the vitamin was lacking in the diet. However, this approach is time consuming and not suited to clinical practice. While the recognition of a vitamin deficiency is frequently based on clinical signs, confirmation of the diagnosis and severity may be assessed by one of the following four procedures:

1. Measurement of the concentration of the vitamin in biological fluids, such as plasma, or tissues such as liver.
2. Oral administration of the vitamin to the dog or cat and measurement of the urinary excretion of the vitamin or one of its metabolic products as an index of the saturation of body tissues.
3. Measurement of a compound in a biological fluid that requires the vitamin for its metabolism, either with or without loading of the precursor. Formiminoglutamic acid and methyl malonic acid are such examples used for the assessment of folate and cobalamin status.
4. Enzyme stimulation tests in which the rate of a reaction is measured before and after the addition of the vitamin, which is a coenzyme in the reaction (e.g., erythrocyte glutathione reductase activity test for riboflavin, transketolase test for thiamin, aminotransferase stimulation tests for vitamin B_6).

Vitamin deficiencies were first recognized in dogs about 75 years ago, and dogs played a seminal role in the discovery and differentiation of vitamins A and D. They were also used for the assay of human foods for niacin. Despite this long history, quantitative requirements for many of the vitamins either have not been determined or have been determined for only one physiological state. The contribution of ingredients in foods for dogs and cats to the total vitamin intake is often not known. This latter situation is exacerbated by the commercial practice of adding a common vitamin premix to many diets and neglecting the contribution from the major food ingredients. Adverse effects have been observed when dietary ingredients naturally contain high levels of certain vitamins. However, unlike many other essential nutrients, moderate excesses of vitamins (up to 10 times the requirement for most vitamins) do not compromise the animal.

Vitamins are arbitrarily divided into those that are soluble in lipids and those that are soluble in water. While this subdivision has little to do with functional roles, it does have relevance to absorption from the gut. Fat-soluble vitamins are absorbed along with food lipids and often are associated with them. Any disturbance of normal lipid absorption negatively impacts on uptake of fat-soluble vitamins from the gut. At high concentrations, most water-soluble vitamins are absorbed by passive diffusion, but at low concentrations absorption frequently occurs by Na^+-dependent adenosine triphosphatase (ATPase) saturable active transport systems.

The vitamin nutrition of dogs is similar to that of most other mammals, and dogs served as models for humans in many early studies on vitamins. Dogs played an important role in the demonstration that pellagra in humans was due to niacin deficiency, rather than a transmissible disease (Car-

penter, 1991). In distinction to dogs, cats possess a number of idiosyncrasies in their vitamin nutrition, particularly with respect to vitamins A and D and niacin (Morris, 2002).

In establishing the nutritional requirement for a vitamin, some index (e.g., maximal enzyme activity or minimal excretion of a compound) specific for that vitamin has to be assessed. A precise requirement requires a response curve generated from supplementation with various concentrations of vitamin. For a broken-line response curve, a minimum of four concentrations (two below and two above the requirement) is required. There are few examples in which such responses have been generated to estimate a vitamin requirement for dogs or cats.

In this chapter, the basis on which a vitamin requirement is derived is stated. However, too frequently this is a relatively crude criterion (e.g., body weight [BW] gain) rather than a specific function of the vitamin, such as the activity of an enzyme for which the vitamin plays an integral role as a coenzyme. Much of the research on vitamins in dogs, and to a lesser degree in cats, was done with the objective of understanding the function of the vitamin, rather than of determining a requirement for that species. In addition, the preponderance of the research was done in the early and middle parts of the last century, often when purified vitamins and modern analytical tools were not available.

In humans, as many as one-third of the mutations in a gene result in the corresponding enzyme having an increased Michaelis constant (K_m) or a vitamin-derived coenzyme or substrate resulting in a lower rate of reaction (Ames et al., 2002). When the coenzyme is derived from a vitamin, high-dose vitamin therapy stimulates the variant enzyme. There are indications that similar genetic abnormalities, especially in relation to cobalamin, may occur in dogs and cats, but a discussion of these is outside the scope of this chapter.

In many early studies on vitamin A, thiamin, and riboflavin requirements for dogs, the vitamins were administered on a BW basis. Where BW data have been available, these vitamins were corrected to a dietary energy basis. In Tables 15-2 through 15-14, the minimal requirement (MR), recommended allowance (RA), adequate intake (AI), and presumed safe upper limit (SUL) of each vitamin are listed. The values have been calculated from the primary source using a standard dog or cat with an assumed fixed energy intake. Because vitamin requirements are related to metabolic BW and energy intake, expression of vitamin requirements on a direct BW basis can introduce large errors (Rucker and Steinberg, 2002). Thus requirements listed on a direct BW basis in the aforementioned tables are appropriate only for the BW of the animal defined. The minimal allowances for many of the vitamins are similar to those proposed by the National Research Council (1985, 1986), meaning that no significant studies since then permit another value to be proposed. The allowances in this publication are also similar to many of those proposed by Burger (1993) and ABGE (1989) for dogs.

The proposed minimal concentrations and amounts of the vitamins in Tables 15-2 through 15-14 are the total bioavailable forms of the vitamins present in the diet (contributed by natural ingredients and vitamin premixes) at the point of consumption. Because the natural forms of some vitamins have low bioavailabilities, the proposed amounts will generally be adequate when the majority of the vitamin is from a vitamin premix. However, when a vitamin is contributed mainly by food ingredients, the minimal concentration in the tables should be modified by a suitable factor to account for bioavailability. For a discussion of the bioavailability of vitamins from various foods, refer to Baker (1995).

When comparing analytical values of vitamins in a diet with concentrations given in the tables, the source of the vitamin and its bioavailability must also be evaluated. To propose a single value for a vitamin that would account for its bioavailability from all food ingredients is only misleading and gives a false assurance of adequacy, but could lead to gross overformulation. The RAs provide about 1.25 times the requirements to allow for individual animal variation.

VITAMIN A

In nature, all of the vitamin A ingested by animals originates from carotenoids synthesized by plants. The conversion of carotenoids to vitamin A requires oxidative cleavage of the carotenoid molecule. Although the existence of the enzyme β-carotene 15,15′-dioxygenase that catalyzes the symmetrical cleavage has been known for more than 40 years, the enzyme has not been isolated to date. Recently the gene for β-carotene 15,15′-dioxygenase was cloned from chicks and mice (Wyss et al., 2000, 2001). Also the complementary DNA (cDNA) from mice encoding the dioxygenase that catalyzes the asymmetrical oxidative cleavage at the 9′,10′-double bond has been identified (Kiefer et al., 2001). This enzyme catalyzes the formation of β-apo-10′-carotenal and β-ionone. In addition to carotenoids, the enzyme also cleaves lycopene.

Nearly a century ago, Mellanby (1919) used dogs to distinguish between "an antirachitic factor that is either fat-soluble A, or has a somewhat similar distribution to fat soluble A"—the functional roles of vitamins A and D present in cod liver oil. Although the zoological classification of dogs and cats places then both in the Carnivora, only dogs have the ability to use carotenoid precursors of vitamin A (Ahmad, 1931; Rea and Drummond, 1932; Gershoff et al., 1957). Turner (1934) showed that dogs given 150 g of fresh carrots in addition to a basal diet had higher concentrations of vitamin A in their livers and kidneys than dogs given the basal diet alone and similar concentrations to dogs given the basal diet with added cod liver oil. Cats are unable to convert β-carotene or any other carotenoids to vitamin A, whether they are present in the diet or administered parenterally. Ferrets, another carnivore species more closely related to cats than dogs, inefficiently utilize β-carotene as a

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precursor of vitamin A. The retinol equivalent of β-carotene for ferrets is less than one-fifteenth that of retinol on a weight basis (Lederman et al., 1998).

Absorption, Transport, and Storage

Vitamin A contained in animal tissues and other foods is released from proteins in the stomach through the action of pepsin and becomes associated with lipid aggregates. (See Chapter 5 for a discussion of fat digestion and absorption.) In the small intestine, dietary retinyl esters are hydrolyzed by pancreatic lipase and the intestinal brush border enzyme phospholipase B (Harrison and Hussain, 2001). Free retinol is taken up by enterocytes, probably by a protein-mediated diffusion and passive diffusion at physiological concentrations. The overall absorption of vitamin A is of the order of 80-90 percent (Olsen, 2001). After uptake by the enterocyte, free retinol is sequestered by cellular retinol-binding proteins (CRBPs), which are fatty acid-binding proteins, to form a complex. Two CRBPs have been identified and purified that bind all-*trans* retinol, but it appears that CRBP-II is the one mainly involved in the intestinal mucosa. Retinol attached to CRBP-II may either undergo esterification to form a retinyl ester or be oxidized to retinal.

Carotenoid absorption has an absolute requirement for bile salts independent of its dispersion in a suitable micelle. The efficiency of absorption of carotenoids in food by humans is of the order of 50-60 percent and decreases markedly with dose (Olsen, 2001). Cats are able to absorb orally administered β-carotene but are not able to convert it to retinol (Schweigert et al., 2002). In species that utilize carotenoids, these carotenoids, along with preformed retinol from the diet, are largely converted to retinyl esters in the small intestinal mucosal cells. These cells then release chylomicrons into the lymph that contain a mixture of triacylglycerols, apolipoproteins, and retinyl esters along with unesterified retinol. In their passage into the general circulation, chylomicrons are stripped of their triacylglycerols by lipoprotein lipase, and the remnants that contain retinyl esters, cholesterol esters, and several apolipoproteins are taken up by endocytosis into the liver and, to a lesser extent, other tissues. Within the liver, retinyl esters are hydrolyzed, and free retinol is translocated by a cellular retinol-binding protein 1 (CRBP-I) to the endoplasmic reticulum. The endoplasmic reticulum contains both lecithin:retinol acyltransferase (LRAT) and acylcoenzyme A:retinol acyltransferase (ARAT), which results in synthesis of retinyl esters—primarily stearate, oleate, and linoleate. These esters are stored within parenchymal cells in vitamin A-containing globules.

Liver is the main storage site for vitamin A in both cats and dogs. While the kidneys of cats contain much higher vitamin A concentrations than other species (Lowe et al., 1957; Moore et al., 1963), the quantitative storage in kidneys is small compared to hepatic storage. However, renal vitamin A may be held more tenaciously during vitamin A depletion than that in liver. In most species including humans and rats, vitamin A in the liver is released in combination with retinol-binding protein (RBP). Pre-RBP is synthesized in parenchymal cells of the liver, and after removal of a 3,500-Da (dalton) polypeptide, the resulting apo-RBP binds all-*trans* retinol, and the complex (holo-RBP) is secreted into the plasma. In humans approximately 90 percent of the RBP is saturated with retinol and largely complexed with transthyretin, which also binds thyroid hormones. The half-life of RBP in dogs and cats has not been measured, but in humans it is 11-16 hours.

In most species including humans and rats, circulating retinyl compounds in plasma are in the form of holo-RBP, and only in toxic states are retinyl esters significantly elevated. In most carnivores including dogs and cats, a large proportion of the total plasma retinyl activity occurs as retinyl esters, particularly retinyl palmitate and stearate (Schweigert et al., 1990a,b). In canines and mustelids, 40-99 percent of the total vitamin A in plasma may be due to retinyl esters (Schweigert et al., 1990a), and similar values can occur in cats (Freytag et al., 2003). The exceptions to this generalization are the family Hyaenidae and suborder Pinnipedia that have only retinol in their plasma. Retinyl esters are transported in plasma combined with low-density lipoproteins.

Two mechanisms have been proposed for the uptake of vitamin A by cells from the plasma: one involves a cell surface receptor on the exterior of the cell in contact with the plasma that strongly binds holo-RBP; the other does not. The first mechanism proposes the binding of holo-RBP to the receptor and receptor-mediated endocytosis internalizes the holo-RBP. Apo-RBP is split from retinol and released into the cytoplasm. In the second proposed mechanism demonstrated in keratinocytes, retinol dissociates from RBP and is taken up directly by the lipid membrane into the cell. Presumably in dogs and cats, cells take up retinol combined with RBP.

Besides the RBP in plasma, and CRBP-I and CRBP-II, a number of other binding proteins of retinoids have been identified. These include the cellular retinoic acid-binding proteins (CRABP) type I and II and the cellular retinaldehyde-binding protein (CRALBP), the interphotoreceptor retinol-binding protein, and epididymal retinoic acid binding protein (E-RABP). The retinoid-binding proteins have a number of functional roles including sequestering retinoids in hydrophobic cavities and protecting them from undesirable reactions such as oxidation; serving as transport proteins for retinoids; and acting as coligands for enzymatic transformation of the retinoids.

The efficiency of absorption of dietary vitamin A has not been measured in cats and dogs but, in other species, is of the order of 0.8 to 0.9 depending on the presence and digestibility of fat in the diet. Of the vitamin A that is absorbed, about 0.3 to 0.6 is stored and the remainder is either conjugated or oxidized and excreted in feces and urine.

Morgan and Bentley (1943) were the first to show that dogs excrete vitamin A in urine. Excretion of 15 to 63 percent of the ingested vitamin A occurs in urine (mainly as retinol and lesser amounts of retinyl palmitate or oleate (Schweigert et al., 1990c; Schweigert and Bok, 2000). Much smaller amounts are excreted in the urine of cats (Freytag et al., 2003).

In most literature on dogs and cats, vitamin A requirements have been expressed in terms of the international unit (IU). This terminology does not account for the ability of dogs to utilize carotenoids as precursors for vitamin A, just as humans do. For humans, the use of IU has been largely discontinued in favor of the expression of vitamin A potency in terms of retinol equivalents (RE) (WHO, 1966). When vitamin A activity is expressed as RE, 1 RE is equal to 1 μg of all-*trans* retinol. In contrast, 1 IU of vitamin A is equivalent to 0.344 μg of pure all-*trans* retinyl acetate (0.3 μg all-*trans* retinol). 1 IU is equal to 0.3 RE.

The efficiency of utilization of dietary carotenoids is species-dependent. Even though dogs appear to utilize β-carotene from carrots efficiently (Turner, 1933; Bradfield and Smith, 1938), a retinol equivalency has not been defined. In humans, 21 μg of β-carotene is required to provide 1 RE (West, 2000). For cats, there is no retinol equivalency for β-carotene, therefore, 1 RE for cats is equal to 1 μg of all-*trans* retinol.

Because retinol is highly susceptible to oxidation, it is not used directly in commercial dog and cat foods but is esterified to protect the free hydroxyl group. An ester (acetate or palmitate) is then formed into beadlets for further protection. In one procedure, the retinyl ester (as an oil) is emulsified in a gelatin-starch-glycerin matrix (often with antioxidant added) and formed into a beadlet by spraying the matrix into a tower in which there is an updraft of cold air and starch. By addition of a sugar to the emulsion, cross-linking with the gelatin occurs, which reduces the water solubility of the beadlet and allows it to sustain higher temperatures and friction during expansion, drying, and enrobing processes. The losses in these processes are related directly to the temperature of expansion and drying. Losses of vitamin A potency also occur with storage, requiring manufacturers to overformulate with vitamin A to ensure adequate concentrations when the product is consumed. The industry-average monthly losses on storage have been given as retinyl acetate (oil), 35 percent; non-cross-linked beadlet, 30 percent; cross-linked beadlet, 8 percent (Anonymous, 1998).

Biological Function

Five primary functions of vitamin A have been identified: vision, growth, cellular differentiation, morphogenesis, and immune function. All of these functions can be maintained with dietary retinol, retinal, or retinaldehyde since these compounds are interconvertable by animals. Retinal is readily oxidized to retinoic acid, but animals cannot reduce retinoic acid; so, functions that require retinol, such as vision and reproduction cannot be satisfied by retinoic acid. However, retinoic acid is capable of supporting all other functional roles of vitamin A.

Vision

The involvement of vitamin A in vision has been extensively studied and recently reviewed by Saari (1994). The cascade of the visual cycle begins with 11-*cis* retinal, attached as a protonated Schiff's base of a lysine residue of rhodopsin, receiving a photon of light, which leads to a series of conformational changes resulting in the production of metarhodopsin II. Metarhodopsin II reacts with transducin, a G protein, leading to an activation of cyclic guanosine monophosphate (cGMP) phosphodiesterase, which in turn hydrolyzes cGMP to GMP. The reduction in cGMP, which maintains open sodium channels in the cell membrane, leads to hyperpolarization of the plasma membrane and generation of a nerve impulse. Because retinoids are efficiently recycled in the visual process, the vitamin A requirement for vision is only a small fraction of the total daily requirement for the vitamin.

Growth

The earliest assays for vitamin A were based on the growth of rats given a purified diet to which various "fat-soluble A"-containing foods were added. The subsequent availability of retinoic acid, which maintained growth but not vision (or reproduction in most species), indicated that these were separate functions of vitamin A. Rats can be maintained on low doses of retinoic acid, and when dosing is withheld, growth ceases due to a loss of appetite that occurs 1-2 days after withdrawal of retinoic acid. Presumably the failure of growth in vitamin A-deficient cats and dogs is due to the same mechanism.

Cellular Differentiation

One of the earliest recognized histopathologies of vitamin A deficiency was the replacement of columnar mucus-secreting cells lining the respiratory, gastrointestinal, and reproductive tracts with keratinized squamous cells. Subsequently, it was demonstrated that the addition of vitamin A to vitamin A-deficient keratinizing cells in tissue culture induced their differentiation to mucus-secreting cells. These changes in cells are produced by retinoids through the oxidation of all-*trans* retinol associated with the CRBP to all-*trans* retinoic acid. Similarly it is proposed that retinol bound to CRBP can be isomerized to 9-*cis* retinol and in turn oxidized to 9-*cis* retinoic acid. The all-*trans* or 9-*cis* retinoic acid is transported to the nucleus where it is bound to either a retinoic acid receptor (RAR) or a retinoid X receptor (RXR). The

hormone response elements in the DNA for RXR and RAR have been identified as the same consensus sequence. RXR and RAR also have close similarities to other nuclear hormone receptors. Of the two receptors, RXR has the broadest action and in the absence of 9-*cis* retinoic acid forms heterodimers with the vitamin D receptor (VDR), the thyroid receptor (TR), and RAR but only when the latter are charged with their respective ligands, namely, 1α,25-dihydroxyvitamin D, triiodothyronine, and all-*trans* or 9-*cis* retinoic acid (Olson, 2001). Genes for several proteins including phosphoenolpyruvate carboxykinase, have been identified that contain response elements for retinoid receptors.

Morphogenesis

Retinoids play a major role in morphogenesis through retinoid receptors and cellular retinoid-binding proteins that are expressed in the developing fetus in a temporally dependent manner in various parts of the embryo (Olson, 2001). Most research on vitamin A and embryonic development has been done with nonmammalian species, but retinoic acid has been shown to be a powerful morphogen in mammals (Maden, 1994). Retinoids not only induce normal development of the fetus but in large amounts induce fetal abnormalities. Therefore, both a lack and an excess of vitamin A in the diet during pregnancy can lead to fetal abnormalities.

Immune Response

Many nutrient deficiencies are associated with a reduction in, or delayed immunological response to, various antigens. In rats the primary immune response to protein antigens is markedly reduced in vitamin A deficiency, but the immunological memory required for a secondary response is not adversely affected (Ross and Hammerling, 1994). The immunological response to some viruses is impaired in vitamin A deficiency and restored on repletion

Dogs

Signs of Deficiency

Vitamin A deficiency in dogs was one of the first vitamin deficiencies identified and studied. Clinical signs in dogs are similar to those produced in other species. These signs include anorexia, body weight loss, ataxia, xerophthalmia, conjunctivitis, corneal opacity and ulceration, skin lesions, metaplasia of the bronchiolar epithelium, pneumonitis, and increased susceptibility to infections (Steenbock et al., 1921; Stimson and Hedley, 1933; Frohring, 1935a,b, 1937; Crimm and Short 1937; Russell and Morris, 1939; Singh et al., 1965). In young growing dogs, defective remodeling of the cranial foramina produces stenosis of the cochlear nerve; degeneration of cochlear neurons, accompanied by bony growth in the modiolus; overgrowth of the internal periosteal layer of the capsule; and degeneration of the organ of Corti and sensory epithelium of the semicircular canals, resulting in deafness (Mellanby, 1938). Prolonged experimental deficiency may also result in similar damage to the optic and trigeminal nerves.

Requirements

Fat-soluble A was one of the first vitamin deficiencies intentionally induced in dogs (by Mellanby in 1918) at a time when the existence of the two fat-soluble vitamins A and D was not known. Steenbock et al. (1921) demonstrated that a diet deficient in fat-soluble "vitamine" produced ophthalmia in dogs that could be prevented or cured by cod liver oil. Later, Frohring (1935a) demonstrated that the addition of carotene to a vitamin A-free diet allowed normal growth and cured xerophthalmia in puppies, indicating that dogs utilize carotene as a precursor of vitamin A. The same author (Frohring, 1935b, 1937) calculated that the minimal curative dose of vitamin A that effected a definite increase in body weight of depleted puppies was 200 USP (United States Pharmacopeia) units (as carotene)·kg $BW^{-1}\cdot d^{-1}$ for growing dogs. Using a similar depletion approach, Crimm and Short (1937) estimated that the minimal vitamin A requirement (from cod liver oil) of adult dogs was 22 to 47 IU (7 to 14 RE)·kg $BW^{-1}\cdot d^{-1}$. Bradfield and Smith (1938) used the minimal curative dose of Frohring of 200 IU kg $BW^{-1}\cdot d^{-1}$ and found that this intake supported normal growth and some storage in the liver of puppies. Higher intakes of 120, 300, and 600 RE·kg $BW^{-1}\cdot d^{-1}$ resulted in higher concentrations of vitamin A in the liver. These authors also found that 200 IU·kg $BW^{-1}\cdot d^{-1}$ from carrots and carotene in oil gave similar liver concentrations as 200 IU·kg $BW^{-1}\cdot d^{-1}$ from cod liver oil.

There do not appear to have been any quantitative studies on the vitamin A requirements of dogs that used a purified source of vitamin A and measured the concentrations of vitamin A in dogs' liver. Therefore, further refinement of the adequate intake suggested by the NRC (1985) of 303 RE per 1,000 kcal for growing puppies and adult dogs is not warranted. This dietary concentration is equivalent to about 40 RE·kg $BW^{-0.75}\cdot d^{-1}$ for adult dogs at maintenance and twice that value for growing puppies. No published experimental studies were found on the retinol requirements for pregnancy and lactation so the same dietary concentration for growth (303 RE per 1,000 kcal) is recommended for bitches during pregnancy and lactation.

Hypervitaminosis

Dietary carotenoids are assumed to have a low toxicity for dogs. Toxicity from the ingestion of excessive amounts of retinoids may be acute or chronic or produce teratological changes. The unit of vitamin A used in this review of hy-

pervitaminosis is micrograms of retinol (1 IU vitamin A has the same activity as 0.3 μg retinol).

Hendricks et al. (1947) examined the effects of optimal and excess vitamin D in the presence of optimal and excess vitamin A. These authors reported no adverse effects in three weaned cocker spaniel puppies given a diet containing 3,030 μg retinol·kg $BW^{-1}·d^{-1}$ in the presence of normal intakes of vitamin D for about 10 months. However, only one dog was necropsied and radiographs of the other dogs were not taken. Over the 10-month period, 40 percent of the oral intake of vitamin A by the dogs given 3,030 μg·kg BW^{-1} was stored.

Maddock et al. (1949) gave a litter of 2-month-old greyhound puppies a diet of milk, bread, horsemeat, and dog chow with an occasional supplement of cod liver oil (amount and frequency not stated). Three puppies acted as controls, and two puppies received 90,000 μg retinol (300,000 IU of vitamin A)·kg BW^{-1} 6 days a week. After 30 days, the treated dogs showed inappetance and a marked decline in body weight. Both dogs exhibited hyperesthesia of the skin, pain on palpation of the epiphyses of the front legs, and a reluctance to stand and moderate exophthalmia. Radiography of the long bones of the treated dogs showed a marked narrowing of the epiphyseal cartilage and a reduction in the density and thinning of the cortices of the femur, tibia, radius and ulna. Histological examination of the bones showed an imbalance in the normal remodeling processes. Degenerative lesions were found in arteries and veins of the tissues examined.

Cho et al. (1975) gave Labrador retriever puppies (about 6 kg BW at the beginning of the test) a commercial diet and either vitamin A palmitate alone or in a combination vitamin A, D, and E preparation by either oral or parenteral (intramuscular injection) routes. Treatments were as follows: group I, a control diet; group II, 30,000 μg retinol·kg BW^{-1} once a week parenterally for 10 weeks, then oral 90,000 μg retinol·kg $BW^{-1}·d^{-1}$ for 88 days; group III, 60,000 μg retinol·kg BW^{-1} once a week parenterally for 14 weeks; group IV, 30,000 μg retinol·kg BW^{-1} once a week parenterally in a vitamin A-D-E combination; group V, 60,000 μg retinol·kg BW^{-1} once a week parenterally in a vitamin A-D-E combination (also supplying 3,750 mg of vitamin D_2 and 100 IU of vitamin E). One dog from group I was given the control diet for 72 days and then 90,000 μg retinol·kg $BW^{-1}·d^{-1}$ orally for 48 days. By the 11th week, all puppies in groups II, III, IV, and V were dehydrated and had central nervous system depression. Bloody diarrhea, vomiting, and ocular discharge were occasionally observed in dogs in groups II and V. By the 14th week, dogs from group II were severely dehydrated, emaciated, depressed, and reluctant to walk and had roughened coats. They also exhibited severe pain responses in the regions of the carpal and tarsal joints. Fatty liver was the only gross pathologic finding. Main radiographic and histologic findings related to the bones. Long bones were decreased in length and thickness because of premature closure of the epiphyseal plate. Epiphyseal plates were markedly narrowed or had disappeared in the long bones, particularly the tibia and radius. Osteoporosis of the diaphysis, particularly involving the radius and ulna was also present. Dogs given the vitamin A-D-E combination appeared less severely affected than dogs given the vitamin A alone, although they were euthanized earlier than those dosed with oral vitamin A.

Cline et al. (1997) reported no adverse changes in the tibia bone measured by computer tomography resulting from feeding diets containing 4,500, 15,000, 34,800, or 67,500 μg retinol per 1,000 kcal ME to adult dogs for 1 year. The authors concluded that a dietary concentration of 67,500 μg retinol per 1,000 kcal ME was not detrimental to normal bone health in adult dogs for one year, and canines appear less sensitive to excess vitamin A in the diet than do some other mammals.

Goldy et al. (1996) gave 10- to 12-month-old beagles either a basal diet containing 600 μg retinol·kg^{-1} diet or diets with an additional 9,000 15,000, 30,000, 60,000, or 120,000 μg retinol·kg^{-1} diet added (analysis of the diet gave values of 180 to 37,500 μg retinol per 1,000 kcal ME). Sufficient amounts of the diet were given to maintain ideal body weight (amounts not stated) for 26 weeks. Hepatic concentrations of retinol at 26 weeks were linearly related to the dietary concentration of retinol. Dogs receiving the diet containing 37,500 μg retinol per 1,000 kcal had significantly higher plasma concentrations of retinol, RBP, and prolonged activated prothrombin times. The authors did not report the concentrations of retinyl esters in plasma, or possible adverse effects of the high intakes of vitamin A on bone, but suggested a vitamin A tolerance of 60,000 μg retinol·kg^{-1} diet for dogs at maintenance.

As dogs efficiently store excess vitamin A in the liver, (Hendricks et al., 1947) an as the concentration of vitamin A in the liver of dogs (and cats) increases with time of exposure to diets with excessive levels (Goldy et al., 1996), only lifetime studies will demonstrate a SUL. The study by Cline et al. (1997) indicated a SUL for tibial bone health of adult dogs for a relatively short period (1 year) in the total life of some dogs of 67,500 μg retinol per 1,000 kcal of diet, while the study by Goldy et al. (1996) indicated that a diet containing a lower concentration of vitamin A (37,500 μg per 1,000 kcal) given to dogs for half the time (26 weeks) induced prolonged activated partial prothromboplastin times and elevated retinol binding protein concentrations. These authors suggested a dietary vitamin A tolerance of about 16,000 μg per 1,000 kcal ME or 64,000 μg·kg^{-1} diet of 4 kcal·g^{-1}.

Two reviews (Kwacho, 1989; Power and Ihrke, 1990) on retinoids in veterinary dermatology provide information on therapeutic considerations and on effects of oral retinoid therapy. These reviews, however, provide limited insight into maximal safe levels as defined in this report.

The NRC (1987) proposed a presumed maximal safe level for a number of species including dogs of 10 times the

requirement (i.e., 12,120 μg retinol·kg^{-1} diet for dogs). Because carnivores appear to have a higher tolerance for excessive intakes of vitamin A even though a SUL has not been defined, it is suggested that an upper limit of 15,000 μg retinol·kg^{-1} diet of 4 kcal·g^{-1} be used for puppies. For adult non-breeding dogs, it is proposed a safe upper limit of 64,000 μg retinol·kg^{-1} diet (4 kcal·g^{-1}) be adopted. It is recognized that dogs appear to be less sensitive to excessive intakes of vitamin A than non-carnivores or the toxicity has not been as well documented as in humans. Consumption by human adults of 7,500 to 15,000 μg retinol·d^{-1} for several months or more can produce multiple adverse effects. Adverse effects occur in children with intakes as low as 450 μg retinol·kg^{-1}·d^{-1} and maternal intakes as low as 7,500 μg retinol were associated with birth defects (Hathcock et al., 1990).

There is little information on the effect of excess vitamin A on pregnancy in dogs other than the study of Wiersig and Swenson (1967), which reported that 37,500 μg retinol·kg BW^{-1}·d^{-1} administered for days 17 through 22 of pregnancy induced teratological changes in puppies. Until a study is undertaken in which bitches are continuously exposed before and through pregnancy to elevated vitamin A intakes, a SUL for reproduction cannot be defined. In the interim, the level proposed for puppies (15,000 μg retinol·kg^{-1} diet of 4 kcal·g^{-1}) is also suggested for breeding bitches.

Cats

Signs of Deficiency

Scott et al. (1964) reported conjunctivitis, xerosis with keratitis and vascularization of the cornea, photophobia, delayed pupillary response to light, formation of cataracts, and retinal degeneration in cats given purified diets based on casein as a protein source for 6 to 20 months. Supplementation of these diets with vitamin A did not reverse the clinical signs and the authors concluded that "the continual feeding of casein made it difficult for the cat to utilize vitamin A." These diets were deficient in taurine, and the observed retinal degeneration was undoubtedly a consequence of taurine deficiency rather than of vitamin A. In another study, Scott et al. reported that in vitamin A deficiency induced by a diet containing meat, no retinal degeneration occurred, although conjunctivitis generally appeared. Retinal degeneration was probably the basis for higher estimates of the vitamin A requirements of cats than other mammals by workers such as Scott (1971).

Gershoff et al. (1957) also used a casein-based diet and reported that the time required for appearance of clinical signs of deficiency was related to the age of the cat when the deficient diet was fed. The reported early clinical signs of vitamin A deficiency were weight loss, a serosanguinous exudate about the eyes, and muscle weakness. Squamous metaplasia of tissues appeared in the following order: conjunctiva, salivary glands, endometrium of the uterus, and respiratory tract. Subpleural cysts lined with squamous epithelium, without bronchial communication, were also observed. Metaplasia of the trachea and bronchi were observed after exposure of more than 6 months to the deficient diet. Extensive infectious sequelae were common in the lung and occasionally in the conjunctiva and salivary glands. Marked hypoplasia of the seminiferous tubules with complete absence of spermatocytes was found in young male cats given the deficient diet. In 6 of the 15 deficient cats, the acinar tissue of the pancreas had loss of zymogen granules and/or cytoplasmic basophilia.

A detailed study of changes in retinal function of cats given a diet (containing adequate concentrations of taurine, vitamin E, and retinoic acid) but deficient in vitamin A during depletion and recovery has been reported by Kemp et al. (1989). These authors reported that extended vitamin A deficiency led to an abnormal appearance in the tapetal fundus with the formation of a dark brown streak centered in the area centralis. At the time the condition occurred, the sensitivity of the rods was reduced by more than 2 log units and the visual pigment was reduced by more than 90 percent. After vitamin A supplementation, rapid increase and partial recovery of both rhodopsin concentration and sensitivity occurred and the brown color of the fundus faded.

A range of reproductive and developmental disorders in queens including abortions, resorption of fetuses, premature birth, birth of hairless kittens, and cleft palates was observed by Morris (personal communication) in queens given purified diets containing 600 to 1,200 μg retinol·kg^{-1}.

Requirements

Because cats do not utilize carotenoids, they require preformed retinoids in the diet. Therefore, the vitamin A requirement of cats is given in terms of micrograms of retinol rather than RE. Within the range of 1 to 26 percent fat in the diet, absorption of vitamin A as indicated by serum concentrations appears to be positively related to the level of dietary fat (Gershoff et al., 1957). Scott (1971) estimated that the vitamin A requirement of cats (presumably breeding queens) was 300 to 600 μg retinol·d^{-1}. This would be equivalent to a dietary concentration of 2,667 to 5,334 μg retinol·kg^{-1} diet (4 kcal·g^{-1}). Unpublished data (K. Knox, University of Connecticut) suggested that 20 μg retinol·kg BW^{-1}·d^{-1} maintained adequate plasma concentrations (>40 μg·dL^{-1}) in weaned kittens. If these kittens had a body weight of 0.8 kg and consumed 180 kcal·d^{-1}, the concentration in the diet would be 89 μg retinol per 1,000 kcal. The next highest concentration used (256 μg retinol·kg BW^{-1}) appeared to be more than required. In a long-term study, Morris and Rogers (personal communication) found that 1,200 μg retinol·kg^{-1} diet (267 μg retinol per 1,000 kcal) supported conception in queens but did not support normal fetal development since some of the kittens were born hair-

less or with cleft palates. The next increment used (1,800 μg retinol·kg^{-1} diet (4.5 kcal·g^{-1} or 400 μg retinol per 1,000 kcal) prevented deformities and supported normal kitten development and growth during nursing. These studies indicate that 89 to 400 μg retinol per 1,000 kcal would be adequate for the growth of kittens and 400 μg retinol per 1,000 kcal would be required for pregnancy and lactation. The NRC (1986) proposed a value of 1 mg retinol·kg^{-1} diet (5.0 kcal·g^{-1}) or 200 μg retinol per 1,000 kcal for growing kittens. No new studies have been found since this recommendation was made, and it is proposed as an AI for growth and for maintenance. For pregnancy and lactation, a value 400 μg retinol per 1,000 kcal is proposed. A dietary concentration of 200 μg retinol per 1,000 kcal is equivalent to an intake of 20 μg retinol·kg BW$^{-0.67}$ for adult cats at maintenance and about twice the value for growing kittens on the same basis. A strong positive relationship between the age of cats given commercial diets and liver concentration of vitamin A can be demonstrated. Although the effects, if any, of these high hepatic concentrations of vitamin A are unknown, it would be prudent not to greatly exceed the RAs for vitamin A.

Hypervitaminosis

Naturally occurring cases of hypervitaminosis A have occurred almost exclusively as a consequence of feeding a diet largely or totally of liver to growing kittens (Seawright et al., 1970). The quantity of vitamin A supplied by liver that induced skeletal lesions ranged from 17 to 35 μg retinol·g BW^{-1}·d^{-1}. The addition of 15 μg of vitamin A (as palmitate)·g BW^{-1}·d^{-1} to an all-meat diet over a period of 41 weeks did not induce the skeletal lesions. The next higher level of supplementation (30 μg retinol·g^{-1} BW^{-1}·d^{-1}) produced lethargy after 10 weeks and spondylosis in 24 weeks. The primary lesion of vitamin A excess in growing kittens is extensive osseocartilagenous hyperplasia of the first three cervical vertebrae. These outgrowths restrict movement and affected cats are unable to effectively groom and have unkempt fur (Seawright et al., 1967).

Clark et al. (1970a,b) and Clark (1970, 1973) confirmed these observations and verified that the lesions could be produced with diets containing excessive vitamin A but adequately supplied with calcium. These authors demonstrated that the long bones of affected cats were shorter than normal and osteoporotic, and the epiphyseal plates were damaged. Seawright and Hrdlicka (1974) described a proliferative gingivitis, retarded development of osseous alveolar processes and tooth loss due to excess vitamin A.

Freytag (2001) and Freytag et al. (2003) investigated the teratogenic effect of excess amounts of vitamin A in queens continually exposed to diets containing either 6,000 (control), 306,000, or 606,000 μg retinol/kg diet. Neither of the high-vitamin A diets affected pregnancy rate, nor the number of kittens born per litter. Queens receiving the diet containing 306,000 μg retinol·kg^{-1} had a low incidence of fatal malformations in their kittens. When the dietary concentration was 606,000 μg retinol·kg^{-1}, there was a significant increase in fatal malformations that included cleft palates and other teratogenic defects associated with vitamin A toxicity in mammalian species.

Three of the 15 queens that began exposure to the 306,000-μg retinol diet from 10 to 11 months of age and four of the 15 queens given the 606,000 μg retinol·kg^{-1} diet that were exposed from 2 to 3 years of age had skeletal lesions primarily of the cervical vertebrae. No lesions occurred in the control queens. As a safe upper dietary concentration of vitamin A for queens has not been defined, and, as 306,000 μg retinol·kg^{-1} diet produced pathological changes, it is suggested that queens should not be exposed to dietary concentrations greater than 100,000 μg retinol·kg^{-1}. As these cats were adults, it is suggested that this upper limit also apply to maintenance. A diet that supplied 17 μg retinol·g BW^{-1} from liver (a likely source of excess vitamin A in the diet; equivalent to 302,000 μg retinol·kg^{-1} diet) induced skeletal pathology in kittens (Seawright et al., 1970). As growing kittens are at least equally vulnerable as adults to hypervitaminosis A it is suggested that a safe upper dietary concentration for kittens should also not exceed 20,000 μg retinol per 1,000 kcal. This value is 100 times the proposed adequate intake of retinol for kittens.

VITAMIN D

Vitamin D is a generic descriptor for a group of related secosteroids derived from the cyclopentanoperhydrophenanthrene ring that have antirachitic activity. The two most important members of this group are cholecalciferol (vitamin D_3) and ergocalciferol (vitamin D_2). Vitamin D is not the active form of the vitamin but has to undergo two hydroxylation reactions to the biologically active form of the steroid hormone. Vitamin D functions along with two peptide hormones (parathyroid hormone and calcitonin) in the homeostatic control of calcium, which is essential for the normal functioning of a range of physiological processes including muscle contraction, blood clotting, nerve conduction, intracellular signal induction, and so forth. Vitamin D also plays an important role in phosphorus homeostasis.

Absorption, Transport, and Storage

Vitamin D in the diet is absorbed from the small intestine, and absorption is aided by bile salts. Taurine supplementation is reported to increase vitamin D absorption in preterm human infants (Zamboni et al., 1993). No absorption studies have been reported on dogs and cats, but in rats, baboons, and humans, vitamin D is absorbed by the enterocytes and secreted into the lymphatics associated with chylomicrons (Collins and Norman, 2001). For most animals, vitamin D is a conditional nutrient, synthesized during ultra-

violet B radiation of the skin from 7-dehydrocholesterol, an intermediate in one of the pathways of cholesterol synthesis. For these animals, vitamin D is needed in the diet only when exposure to ultraviolet light is limited.

Vitamin D produced in the skin is transported to the liver by a vitamin D-binding protein (DBP) where it, along with vitamin D absorbed from the diet, undergoes hydroxylation in the 25-position to 25-hydroxyvitamin D (25-OHD). The 25-hydroxylase is a P450-like enzyme that is poorly regulated in most animals, making circulating levels of 25-OHD the appropriate index of vitamin D status in the normal and toxic range. Also, 25-OHD is the major circulating vitamin D metabolite, which facilitates its measurement. From the liver, 25-OHD is transported on DBP to the kidney where a second hydroxylation occurs to give the active form of the hormone 1α,25-dihydroxyvitamin D (1α,25-$(OH)_2$D). The 1α,25-hydroxylase is located in the mitochondria of the proximal tubules of the kidney and belongs to the mixed oxidase class of enzymes. The concentration of 1α,25-$(OH)_2$D in plasma is tightly controlled, mainly through the activity of 1α,25-hydroxylase in the kidney, which in turn is under positive and negative feedback regulation primarily through parathyroid hormone (PTH), but also serum concentrations of 1α,25-$(OH)_2$D, calcium and phosphorus. PTH released in response to low serum calcium stimulates the activity of the 1α,25-hydroxylase and decreases the activity of the 24-hydroxylase. While there is some debate on the role of 24, 25-$(OH)_2$D in mineralization of bone and eggshell production, it has been shown to act negatively on PTH production and is one of the excretory products of vitamin D metabolism.

Biological Function

Responses produced by 1α,25-$(OH)_2$D are mediated by its action on nuclear receptors and nongenomic pathways such as calcium channeling. Many nuclear receptors for 1α,25-$(OH)_2$D have been identified in target tissues not related to calcium homeostasis (Collins and Norman, 2001). The nuclear receptor for 1α,25-$(OH)_2$D is a DNA-binding protein that binds 1α,25-$(OH)_2$D with a high affinity.

The classical target tissues of 1α,25-$(OH)_2$D are those that regulate mineral status. When there is a decrease in serum calcium, the parathyroid gland increases secretion of PTH, which stimulates the 1α,25-hydroxylase to increase synthesis of 1α,25-$(OH)_2$D. These two hormones (PTH and 1α,25-$(OH)_2$D) in concert increase resorption of bone and restore serum ionic calcium concentration. Receptors to 1α,25-$(OH)_2$D have been found in osteoblasts but not osteoclasts, so it is suggested that osteoclastic activity is stimulated through osteoblasts or by nongenomic signal transduction pathways such as opening calcium-gated channels. Dissolution of bone contributes both calcium and phosphorus to the plasma, but the rise in phosphorus is blunted by its larger pool and augmentation of renal excretion induced by elevated PTH levels.

Mellanby (1925) exposed dogs and their diets to mercury vapor lamps and sunlight as sources of ultraviolet radiation. He found only a slight beneficial effect of exposing dogs with their backs shaved to UV light. It was apparent that the response he obtained to UV radiation of dogs was not the large response recorded in humans by Huldschinsky (1919). Similarly, Mellanby found that "some part of the rickets producing influence of oatmeal could be eliminated by direct exposure to UV radiation." Exposure of dogs (Hazewinkel et al., 1987) and cats (Morris, 1999) to UV light results in ineffective synthesis in these species; they are virtually entirely dependent on diet for vitamin D. The skins of dogs (How et al., 1994) and cats (How et al., 1994; Morris, 1999) have low concentrations of 7-dehydrocholesterol compared to species capable of synthesizing vitamin D. However, administration of an inhibitor of the enzyme 7-dehydrocholesterol Δ^7-reductase to cats allowed vitamin D synthesis to occur (Morris, 1999). These observations suggest that the metabolic basis for cats and dogs having a dietary requirement for vitamin D is that 7-dehydrocholesterol is rapidly converted to cholesterol, due to the high activity of the enzyme 7-dehydrocholesterol Δ^7-reductase.

In most species, cholecalciferol (vitamin D_3) is used with equal or greater efficiency than is ergocalciferol (vitamin D_2). The differential utilization has not been investigated in dogs, but, in cats, cholecalciferol is utilized more efficiently than is ergocalciferol to maintain plasma concentrations of 25-OHD (Morris, 2002b). Similar differences between the two forms of the vitamin have also been reported in humans (Trang et al., 1998). Cholecalciferol is also more toxic at an equivalent dose than ergocalciferol. The mechanism of toxicity has not been established, but ectopic calcification of arteries, kidneys, and other soft tissues is believed to be responsible.

Cholecalciferol is generally added to commercial dog and cat foods as beadlets, although spray-dried and drum-dried products are also available. Recoveries after extrusion, drying, and enrobing of vitamin D are much higher than vitamin A and losses on storage much less. Cross-linked beadlets give the highest recovery in processing and lowest rate of loss on storage.

Dietary concentrations of vitamin D were often expressed in terms of IUs, where 1 IU = 0.025 μg of cholecalciferol (vitamin D_3), or 40 IU = 1 μg of cholecalciferol. Since the substitution value of ergocalciferol for cholecalciferol has not been established for dogs, requirements are given in term of micrograms of cholecalciferol.

Dogs

Signs of Deficiency

Since calcium, phosphorus, and vitamin D nutrition interact in the maintenance of normal mineral status and skeletal integrity, there are similarities in the gross clinical

signs resulting from a deficiency of any one of these nutrients. Defective mineralization of the skeleton and lameness are clinical sign common to both calcium and vitamin D deficiencies.

Dogs played a major role as experimental animals in elucidation of the nutritional basis of endemic rickets in children, which was primarily a problem of inadequate vitamin D. Mellanby (1921), in a summary of his studies on rickets (in which nearly 400 puppies were used), stated that rickets occurred more rapidly in fast-growing than slow-growing dogs. Dogs with rickets became lethargic and had a general loss of muscular tone, which did not allow them to run quickly. As the condition progressed, there were large swellings of the epiphyseal ends of the bones and bending of the long bones, the extent dependent on the degree of weight bearing. An early indication of rickets on radiology was a change in shape of the epiphysis of the distal ulna. This became flattened, with a wavy and indefinite outline, and there was an increase in the width of the epiphyseal cartilage and the adjacent newly calcified bone lost contrast.

Malik et al. (1997) reported a case of rickets in a litter of greyhounds that exhibited listlessness, profound muscle weakness, lameness, lateral bowing of the antebrachii, and focal hard swellings proximal to the tarsi and carpi. Radiological examination showed osteopenia, axial and radial thickening of the growth plates, and "cupping" of the adjacent metaphyses. Vitamin D deficiency was confirmed by subnormal 25-OHD concentrations in serum samples.

Requirements

Even though Mellanby (1918) reported nearly a century ago that rickets in dogs could be prevented by inclusion of butter or cod liver oil (but not cottonseed oil) in a rachitogenic diet, there have been no definitive studies to define the minimal vitamin D requirements of puppies. The requirement to prevent adverse clinical signs depends on calcium and phosphorus concentrations in the diet, physiological state of the dog, and size at maturation. Growing animals, because of high demand for calcification of the skeleton, are most sensitive to a dietary deficiency of vitamin D, whereas mature dogs are relatively resistant.

Arnold and Elvehjem (1939a) reported two experiments on the vitamin D requirements of Great Danes. In one experiment, vitamin D was supplied from canned dog food and measured by the chick assay (cholecalciferol); in the other experiment it was supplied as irradiated yeast (ergocalciferol) and measured by a rat assay. The authors proposed a vitamin D requirement of 20 IU per 100 g food of about 3.8 $kcal \cdot g^{-1}$ (5.3 $\mu g \cdot kg^{-1}$ diet of 4 $kcal \cdot g^{-1}$) for growing puppies given a diet containing 9.0 g calcium and 7.5 g phosphorus per kilogram. When 15 g calcium carbonate was added to the diet of one dog, appetite declined after 20 days and it developed rickets. The authors concluded that a Ca:P ratio of 2:1 was less favorable for calcification thatn 1.2:1. The recommendation of 10 to 20 IU vitamin D·kg $BW^{-1} \cdot d^{-1}$ was later made by Michaud and Elvehjem (1944).

Campbell and Douglas (1965) gave three groups of 6- to 10-week-old mongrel pups a basal diet (0.08 to 0.1 percent calcium and 0.13 to 0.15 percent phosphorus) that was composed mainly of meat and unfortified bread. To this basal diet, bone meal was added (group A, control), giving a mineral content of 0.5 percent calcium and 0.3 percent phosphorus; group B received the basal diet alone; and group C received the basal diet plus a daily supplement of either 2.5 µg vitamin D (five pups) or 25 µg vitamin D (two pups). It was not stated whether the vitamin D was in the form of ergocalciferol or cholecalciferol. Control dogs and those in group B had satisfactory body weight gains, but those in group C had decreased food consumption, which was more marked in dogs receiving the higher level of vitamin D. Dogs in group B developed lameness, rachitic changes or bending of the legs, plantigrade stance, and enlargement of the epiphyses. Dogs in group C had similar skeletal changes and persistent lameness. Radiographs of dogs in group B indicated marked osteoporosis. In group C, pathological fractures of the femur, tibia, and pelvis occurred in dogs given both the low and the high vitamin D intakes. Dogs given the control diet maintained plasma calcium in the normal range, but those given the low-calcium diet without vitamin D developed marked hypocalcemia by 12 weeks. Less depression of plasma calcium occurred in dogs given the low, and even less in dogs given the high level of vitamin D supplementation. Plasma phosphorus concentrations were not altered, but alkaline phosphatase was elevated in all groups but control dogs. While this study does not help define vitamin D requirements, it demonstrates that for a calcium-deficient diet, vitamin D facilitates the maintenance of normal plasma levels of calcium.

Kealy et al. (1991) reported a study in which 28 weanling puppies were divided into two groups and given a diet formulated from natural dog food ingredients for 102 weeks. The diet of one group had 60.5 µg $cholecalciferol \cdot kg^{-1}$ added, while the other diet was unsupplemented. No differences between the groups in any of the parameters measured (which included growth, serum calcium, phosphorus, and alkaline phosphatase) were found. This study indicated that natural food ingredients may at times provide adequate vitamin D for growing dogs without supplementation. The NRC (1985) proposed a vitamin D requirement of 2.75 µg of vitamin D per 1,000 kcal for growing dogs. This value is consistent with a recent study (Tryfonidou 2002) which reported no adverse bone pathology in Great Dane puppies given a diet containing 12.5 µg $cholecalciferol \cdot kg\ diet^{-1}$. Since no information was found on the requirements for adult dogs and pregnant or lactating bitches, the same dietary concentrations are recommended, 2.75 µg per 1,000 kcal equivalent to 0.36 $\mu g \cdot kg\ BW^{-0.75} \cdot d^{-1}$ in adult dogs at maintenance.

Hypervitaminosis

Morgan and Shimotori (1943) gave cocker spaniel puppies that had been deprived of vitamin D a single dose of 500 µg of vitamin D (from either tuna liver oil, irradiated ergosterol, or activated animal sterol). A transient hypercalcemia was observed at 4 hours postdosing, and vitamin D was detected in the blood for 3 days to 5 months postdosing. No adverse effects were noted at 12 to 14 months of age, at which time the dogs were given a second dose of 5 mg of ergocalciferol (irradiated ergosterol) or cholecalciferol (animal sterol). Vomiting and diarrhea were observed within 3 days, along with anorexia, lassitude, and weakness. Serum calcium initially declined then rose along with serum phosphorus. In another study, Shimotori and Morgan (1943) gave dogs a single oral dose of either 5,000 µg irradiated ergosterol or 5,000 µg irradiated animal sterol per kilogram of body weight along with radioactive phosphorus, which produced diarrhea and vomiting on the third day after dosing and required the dogs be euthanized. The authors concluded that a massive dose of vitamin D decreased phosphorus turnover in soft tissues but gave a twofold increase in phosphorus turnover in bone.

Hendricks et al. (1947) gave cocker spaniel puppies 5 to 8 weeks of age 250 µg cholecalciferol·kg BW^{-1}·d^{-1} for 8 to 10 months. The puppies had reduced growth rates, transient hypercalcemia, calcification of soft tissue, and excessive mineralization of long bones with an increased diameter of the shafts. In these studies, irradiated ergosterol (vitamin D_2) produced less toxic effects than irradiated animal sterols.

Spangler et al. (1979) reported a study in which 18 dogs were given doses of either 500 or 1,000 µg·kg BW^{-1} of ergocalciferol per day for 6 to 21 days. Food consumption decreased markedly by the 8th day, and the second week of treatment was marked by general loss of condition, dehydration, dry and brittle hair, and muscular atrophy. Two dogs showed severe depression, an inability to rise from the resting position, and eventual coma. Serum calcium and urea nitrogen increased during this period, but serum phosphorus remained within the normal range. Plasma renin increased markedly, but blood pressure showed only a mild increase. Gross and microscopic examination of the kidneys suggested vascular-oriented changes with an ischemic basis. Glomerular vascular poles showed hypertrophy and hyperplasia of juxtaglomerular cells.

Howerth (1983) reported a case of a breeder of toy Pomeranian puppies having 16 of 24 puppies from six different litters die within a month of birth. Affected puppies stopped nursing and became lethargic at 2-3 weeks of age, which was followed by death within 3 days. Necropsy performed on two puppies revealed renal, pulmonary, and vascular calcification. The dams had received a supplement containing 2.25 µg vitamin D (probably cholecalciferol) and 270 µg of retinol (vitamin A), 667 mg calcium lactate, and 167 mg calcium glycerophosphate per day in addition to vitamins present in the dog food (not measured but suggested as 66 µg of retinol and 0.55 µg of vitamin D·kg BW^{-1}·d^{-1}). After the supplement was discontinued, there were no further problems in puppies in subsequent lactations.

Dzanis et al. (1991) reported that administration of pharmacological amounts (0.03 to 0.05 µg·kg BW^{-1}) of 1,25-$(OH)_2D_3$ per os to renally impaired adult dogs resulted in depression in appetite, body weight, and renal function, as well as bone and parathyroid cell atrophy, but without hypercalcemia. Administration of 1,25-$(OH)_2D_3$ to dogs with normal renal function resulted in a marked elevation of serum calcium.

Gunther et al. (1988) investigated the toxicity in dogs of cholecalciferol-containing rodenticides. They gave a rodenticide that supplied either 10 mg or 20 mg cholecalciferol·kg BW^{-1} to each of two dogs. The time taken for onset and temporal progression of clinical signs was similar in all dogs. The dogs became less active 30 hours after consumption; lethargic, weak, and anorectic by 48 hours; recumbent at 60 to 70 hours; and died soon after. Serum calcium and phosphorus were both elevated. Histological findings were in general similar to those reported by Spangler et al. (1979), with the exception of acute hemorrhage of the superficial mucosa of the stomach and small intestine, and foci of necrosis and mineralization of myocytes of the myocardium.

Growing Great Dane dogs given diets containing moderately high concentrations of vitamin D_3 (100 µg cholecalciferol·kg^{-1}) were reported to have lower fractional absorption of calcium than dogs given a diet containing 12.5 µg cholecalciferol·kg^{-1}, despite both diets having the same concentration of calcium (Tryfonidou et al., 2002). These authors reported that dogs receiving the moderately high vitamin D diet had similar concentrations of 25-OHD_3 and 1,25-$(OH)_2D_3$ in their plasma but higher concentrations of 24,25-$(OH)_2D_3$ than dogs given the diet with the 12.5 µg of cholecalciferol·kg^{-1}. They suggested that the turnover rates of 25-OHD_3 and 1,25-$(OH)_2D_3$ were increased, and the elevated concentration of 24,25-$(OH)_2D_3$ in plasma may downregulate the absorption of calcium from the gut in growing Great Dane puppies.

In another experiment (Tryfonidou, 2002) Great Dane puppies were given a diet containing excessive (but sublethal) concentration of cholecalciferol (1,350 µg·kg^{-1}), the plasma concentration of 25-OHD_3 was 30 to 75 times greater, and 24,25-$(OH)_2D_3$ 16 to 18 times greater than in control dogs given a diet containing 11 µg cholecalciferol·kg^{-1}. Plasma concentrations of 1,25-$(OH)_2D_3$ were greatly decreased in dogs receving 1,350 µg cholecalciferol·kg^{-1} diet due to increased activity of renal and small intestinal 24-hydroxylase, and enhanced clearance of 1,25-$(OH)_2D_3$. The ability to upregulate the activity of 24-hydroxylase appears to be critical in large-breed dogs to ameliorate the effects of high, but sublethal intakes of vita-

min D. The plasma concentration of 25-OHD_3 appears to be a less reliable index of vitamin D intake at moderate concentrations than in cats (Morris et al., 1999).

In studies with growing Great Dane puppies (Tryfonidou, 2002), the diet containing 1350 μg cholecalciferol·kg^{-1} promoted similar growth rates as the control diet containing 11 μg of cholecalciferol·kg^{-1}, but produced irregular growth plates and severely disturbed endochondrial ossification. Puppies given the diet containing 100 μg cholecalciferol·kg^{-1} (about 25 μg per 1,000 kcal), also had similar growth rates as control dogs, but had lowered bone turnover and impaired endochondrial ossification on histological examination of the growth plates.

In most species, cholecalciferol is 10 to 20 times more toxic than is ergocalciferol at comparable doses (NRC, 1987), and the same could be expected in dogs. The recommendations of the NRC (1987) of a SUL for long-term (>60 days) feeding for most species was 4 to 10 times the requirement, which is equivalent to 11 to 27.5 μg cholecalciferol per 1,000 kcal. The upper range of 27.5 μg cholecalciferol per 1,000 kcal is greater than the concentration shown by Tryfonidou (2000) to be associated with lowered bone turn-over and impaired endochondrial ossification. It is suggested that a dietary concentration of cholecalciferol should not exceed 20 μg per 1,000 kcal for growing dogs. In the absence of long-term studies on dogs at maintenance and pregnant and lactating dogs it is suggested that these upper dietary concentrations be also applied to these dogs. These values are consistent with the general recommendation of the NRC (1987) that mammals not be exposed to diets containing more than 55 μg cholecalciferol·kg^{-1} for periods longer than 60 days. If a metabolizable energy (ME) value of 4,000 kcal·kg^{-1} is assumed for these diets, this would be equivalent to 14 μg cholecalciferol per 1,000 kcal.

Cats

Signs of Deficiency

Gershoff et al. (1957) reported that severe rickets occurred in kittens given vitamin D-deficient diets containing either 1 percent calcium and 1 percent phosphorus or 2 percent calcium and 0.5 percent phosphorus. Weight gain was less with the latter diet, but rickets were less severe. These authors reported that alkaline phosphatase concentration in plasma increased in the third month, and peaked in the fifth to seventh months, and decreased through the 21st month. Serum calcium and inorganic phosphorus concentrations decreased markedly during the severe phase of rickets in kittens given the 1 percent calcium and 1 percent phosphorus diet.

Morris (1999) found that the time taken for clinical signs of vitamin D deficiency to appear in kittens given a purified vitamin D-free diet (0.8 percent calcium and 0.6 percent phosphorus) depended on the kittens' initial stores of vitamin D. Kittens from queens receiving a diet containing a high level of vitamin D (400 μg cholecalciferol·kg^{-1}) during pregnancy and lactation were able to complete their growth phase without clinical signs of vitamin D deficiency, whereas those from queens receiving a lower intake of cholecalciferol (about 25 μg·kg^{-1} diet) had clinical signs of vitamin D deficiency in periods as short as 6 weeks. Similarly when kittens were given a vitamin D-free purified diet containing 14 g calcium·kg^{-1}, clinical signs of deficiency were either delayed or not expressed. Presumably this is due to non-vitamin D-mediated calcium absorption (Lee et al., 1991).

Morris et al. (1994) and Morris (1999) reported that the initial clinical signs of vitamin D deficiency in kittens were a reluctance to move, followed by a progressive posterior paralysis that was initially apparent as a short-stilted gait and progressed to a broad-based gait with marked ataxia and eventual quadriparesis in severely affected cases. About one-third of kittens exhibited enlargement of the metatarsal joints. There was a lack of grooming and eventual reduction in food intake and body weight. Cranial reflexes and positional reflexes were not affected except for depressed conscious proprioception in severely affected cats. In advanced cases of vitamin D deficiency, kittens developed hypocalcemia, often associated with fasciculations of major muscle groups, and had grossly elevated plasma concentrations of intact parathyroid hormone and creatine phosphokinase activity. Cats with posterior paralysis had a reduction in the subarachnoid space of the C2 to C5 vertebrae associated with Wallerian degeneration of axons in the ventral, dorsal, and dorsolateral columns of the spinal cord. These changes were consistent with compression degeneration of neurons resulting from disproportional growth of the spinal cord in relation to the rate of resorption of bone from the foramina of the cervical vertebrae.

Histology of the epiphyses of the femur and humerus showed two types of changes: classical rickets with enlarged growth plates and osteomalacia and fibrous osteodystrophy, or no enlargement of the growth plate but generalized osteopenia.

Requirements

Gershoff et al. (1957) reported that twice weekly oral supplementation with 6.25 μg of cholecalciferol per kitten would prevent the development of rickets in growing kittens given a semipurified diet from 3-6 months of age to 21 months of age. The remission of clinical signs in cats given a vitamin D-deficient diet that survived longer than 12 months suggested that older cats have a lower requirement.

Morris et al. (1999) gave six groups each of seven kittens purified diets containing either 0.0, 3.125, 6.25, 12.5, 18.75, or 25.0 μg cholecalciferol·kg^{-1} diet. (The queens of the kittens had been given a low-vitamin D diet during pregnancy and lactation to reduce the body reserves of vitamin D in the kittens.)

All kittens received the diets from 9 to 21 weeks of age, and two groups (0.0 and 3.125 μg) continued to receive the diets until 34 weeks of age. Plasma concentration of 25-OHD in the kittens was linearly related to the dietary concentration of cholecalciferol. The concentration of 25-OHD in kittens given the 0.0 diet declined significantly from the 9-week values, whereas those of kittens receiving the 3.125-μg diet were significantly greater at 22 and 34 weeks than at 9 weeks of age. Although 3.125 μg of cholecalciferol appeared adequate, the authors suggested a dietary concentration of 6.25 $\mu g \cdot kg^{-1}$ to provide a margin of safety. In another experiment, Morris and Earle (1999) gave growing kittens a purified diet containing 3.125 μg cholecaliferol·kg^{-1}, and calcium concentrations that varied from 3.8 to 8.1 $g \cdot kg^{-1}$ diet with a constant Ca:P ratio. Kittens maintained similar, adequate concentrations of 25-OHD in plasma as in the previous experiment.

Morris (2002b) compared the ability of cholecalciferol and ergocalciferol to elevate 25-OHD concentrations in the plasma of cats when given in the diet or by intravenous injection as an oil emulsion. Independent of the route of administration, the same quantity of cholecalciferol maintained higher concentrations of 25-OHD in plasma than ergocalciferol.

A minimal concentration of 3.125 μg of cholecalciferol·kg^{-1} diet (~4.5 kcal·g^{-1}), or 0.7 μg per 1,000 kcal, appears adequate for growing kittens. However, a concentration of 6.25 μg cholecalciferol·kg^{-1} diet (1.4 μg cholecalciferol per 1,000 kcal) is recommended to provide a margin of safety and is suggested as the recommended allowance. This dietary concentration also appears adequate to support pregnancy and lactation. As the requirements for adult cats at maintenance have not been studied, it is suggested that the same dietary concentration of cholecalciferol (1.4 μg cholecalciferol per 1,000 kcal) be applied for maintenance.

Hypervitaminosis

Reports of hypervitaminosis D in cats have resulted from either accidental ingestion of rodenticides containing cholecalciferol as the active ingredient, consumption of diets based on fish (particularly fish viscera), or errors in diet formulation. These excesses have been associated with cholecalciferol, rather than ergocalciferol, which at least in some species results in lower toxicity at comparable doses than cholecalciferol (Harrington and Page, 1983).

Moore et al. (1988) reported hypercalcemia in three cats that had eaten a rodenticide containing cholecaliferol. Clinical signs included lethargy, anorexia, vomiting, and polydipsia. Similar findings were reported on a single cat by Peterson et al. (1991).

An outbreak of vitamin D toxicosis in cats following consumption of a commercial dry cat food that contained tuna viscera and experimentally induced toxicity were reported by Haruna et al. (1992), Sato et al. (1993), and Morita et al. (1995). Tuna livers have extremely high concentrations of cholecalciferol, and the cat food was reported to contain 1,300 to 1,600 μg vitamin D·kg^{-1} dry matter (DM). Haruna et al. (1992) reported that mainly young cats were affected and exhibited dyspnea, anorexia, vomiting, depression, and renal failure. Unusual calcification was found in the blood vessels, lungs, trachea, digestive tract, kidneys, and osseous tissue. Similar calcification was reported in four affected cats by Sato et al. (1993) who also reported hypercalcemia, and elevated plasma concentrations of 25-OHD, blood urea, and creatinine. Morita et al. (1995), in addition to the above pathology, reported oxalate crystals in the kidneys.

The possible role of high intakes of vitamin D in the production of oxalate urolithiasis in cats was investigated by Sih et al. (2001). These investigators gave 4-month-old kittens and queens purified diets containing either 118 or 846 μg cholecalciferol·kg^{-1} for 18 months. There were no apparent adverse effects of the high-vitamin D_3 diet and no cases of renal pathology were found in biopsy samples. Plasma concentrations of cholecalciferol and 25-OHD_3 were markedly elevated in the queens (424 and 588 nmol·L^{-1}, respectively). The authors concluded that cats are more resistant than other species to cholecalciferol toxicosis when the diet is otherwise complete and balanced.

Price et al. (2001a,b) reported that treatment of rats with biphosphonate following ingestion of toxic amounts of cholecalciferol prevented clinical and pathological signs of toxicity. Although this treatment has not been used with cats or dogs, it would appear to offer a better prognosis than furosemide-corticosterone therapy.

The only study allowing an estimate of the presumed safe maximal dietary concentration of vitamin D for cats is the study of Sih et al. (2001). These authors reported that kittens and adult cats did not exhibit any adverse clinical signs when given a diet containing 846 μg cholecalciferol·kg^{-1} for 18 months. If an ME value of 4,500 kcal·kg^{-1} is assumed for this diet, it is equivalent to a concentration of 188 μg per 1,000 kcal. This concentration is about nine times the SUL suggested for growing dogs.

VITAMIN E

Vitamin E is a generic descriptor for tocol and tocotrienol derivatives exhibiting the biological activity of α-tocopherol. The term "tocopherols" is used to describe all mono-, di-, and trimethyltocols and tocotrienols but is not synonymous with the term "vitamin E" (Chow, 2001). All eight naturally occurring tocopherol compounds isolated from plants have a 6-chromanol ring, with an isoprenoid (phytyl) side chain at carbon 2. Tocopherols have a saturated phytyl side chain, whereas tocotrienols have an unsaturated isoprenoid side chain. There are four naturally occurring tocopherols designated as α, β, γ, and δ according to the number of methyl groups on carbons 5, 7, and 8 of the phenolic ring of the 6-chromanol. α-Tocopherol has methyl groups at carbons 5, 7, and 8; β-tocopherol, at carbons 5 and 8, γ-toco-

pherol at carbons 7 and 8; and δ-tocopherol has only one methyl group at carbon 8. In addition, there are four chiral centers from the phytyl chain (at positions 2, 4′, and 8′), making a total of 8 stereoisomers. Modern terminology for the tocopherols uses the *RS* system of nomenclature of chiral centers instead of the older DL terminology. Naturally occurring α-tocopherol (formerly known as D-α-tocopherol) is now designated as *RRR*-α-tocopherol. This stereoisomer of α-tocopherol is 2D, 4′D, 8′D. Synthetic α-tocopherol (previously known as DL-α-tocopherol) is a mixture of eight stereoisomers and has been designated as all-*rac* α-tocopherol (*rac* = racemic). These eight stereoisomers are 2D, 4′D, 8′D (*RRR*); 2L, 4′D, 8′D (*SRR*); 2L, 4′L, 8′D (*SSR*); 2D, 4′D, 8′L (*RRS*); 2L, 4′D, 8′L (*SRS*); 2D, 4′L, 8′D (*RSR*); 2D, 4′L, 8′L (*RSS*), and 2L, 4′L, 8′L (*SSS*).

The biologically active site on the tocopherol molecule is the 6-hydroxyl group on the phenolic ring, which is capable of donating a hydrogen in reactions with free radicals. In normal metabolism, α-tocopherol is reversibly oxidized to the α-tocopheryl chromanoxy radical and reduced by agents such as glutathione and ascorbate. The α-tocopheryl chromanoxy radical may also form a dimer or trimer or be further oxidized to the α-tocopheryl quinone in the liver. Subsequent reduction of the quinone to a hydroquinone and coupling with glucuronate occurs before excretion in the bile. Alternatively, the hydroquinone can be oxidized to α-tocopheronic acid and, after coupling with glucuronate, excreted in urine or the phytyl side chain may undergo oxidation.

In common with other fat-soluble vitamins, the major route of elimination of tocopherols from the body is via bile and excretion in the feces. In some species, there is significant urinary excretion of α-tocopheronic acid, which is assumed to be produced in the liver.

Absorption

In humans, the majority of α-tocopherol is absorbed via the lymphatics and a small portion is absorbed by the portal system. Absorption occurs primarily in the upper and middle third of the small intestine along with the lipid components of the diet. Absorption is non-carrier mediated and nonsaturable. Factors affecting fat emulsification, such as pancreatic lipase and bile secretion also affect the efficiency of vitamin E uptake from the intestine. Absorption occurs as micelles, and tocopheryl esters (e.g., tocopheryl acetate) are hydrolyzed to free tocopherol during the absorptive process. After the micelle crosses the brush border into the enterocyte, it is incorporated into chylomicrons and secreted into the intracellular space and into the lymphatics. There appears to be no discrimination between the various tocopherols up to chylomicron formation. After the chylomicrons are taken up by the liver, the tocopherols are repackaged into very low density lipoproteins (VLDLs) before secretion into the plasma. At this stage, *RRR*-α-tocopherol is preferentially secreted with the VLDLs to *SRR*-α-tocopherol and *RRR*-γ-tocopherol (Chow, 2001). Secretion of various forms of vitamin E into these lipoproteins and subsequent delivery of the vitamin E to the tissues by these lipoproteins depends on the transfer of vitamin E across membranes. Within cells, a cytosolic protein (α-tocopherol-binding protein) selectively facilitates the incorporation of *RRR*-α-tocopherol into nascent VLDLs, which results in discrimination between the various tocopherol analogues. The relative binding of β-, γ-, and δ-tocopherols to the α-tocopherol binding protein, compared to *RRR*-α-tocopherol as 1.0, is 0.38, 0.09, and 0.02, respectively (Hosomi et al., 1997).

During the conversion of VLDLs to low-density lipoproteins (LDLs), there is a transfer of tocopherols, and similar exchange occurs with the high-density lipoprotein (HDL) fraction. Exchange also takes place between lipoproteins, liposomes, and erythrocytes. Parenchymal cells that have a large storage capacity primarily take up tocopherols, but the mechanism of uptake by these cells has not been elucidated. While plasma concentrations of α-tocopherol decrease when animals and humans are given low-tocopherol diets, in humans the concentration can be raised only about two- to threefold, regardless of the duration and amount of supplementation. The lack of response does not appear to be a lower efficiency of absorption of large doses, but newly absorbed vitamin E in part replaces the α-tocopherol in circulating lysosomes and there is an increased rate of plasma disappearance with increasing dose (Traber et al., 1998).

Biological Function

Vitamin E is the major lipid-soluble antioxidant present in plasma, erythrocytes, and tissues where it functions as a scavenger of free radicals and thus prevents free-radical or oxidative damage to polyunsaturated fatty acids (PUFAs) in thiol-rich proteins of membranes and nucleic acids. Tocopherols act as donors of hydrogen from the 6-OH group for the reduction of free radicals. Free-radical reactions are ubiquitous in biological systems and are associated with energy metabolism, biosynthetic reactions, natural defense mechanisms, detoxification, and intra- and intercellular signaling pathways. Support for the antioxidant role of vitamin E in vivo also comes from observations that synthetic antioxidants can either prevent or alleviate certain clinical signs of vitamin E deficiency diseases.

There are many potential adverse effects of oxygen and its reactive products, and cells have developed a number of defensive enzymatic and nonenzymatic systems. These systems include (1) direct interaction of ascorbic acid, glutathione, and other reducing agents with oxidants; (2) scavenging of free radicals and singlet oxygen by vitamin E, ascorbic acid, carotenoids, superoxide dismutase, and other systems; (3) reduction of hydroperoxides by glutathione peroxidase and catalase; (4) binding or removal of transition

metals by proteins such as ferritin, transferrin, ceruloplasmin, albumin, and other chelators; (5) separation or prevention of reactive oxygen species from reaching specific sites; and (6) repair of oxidative damage by dietary nutrients and metabolic activities (Chow, 2001).

In cells, α-tocopherol with its high lipid solubility preferentially partitions into the membrane bilayer where there is the highest concentration of PUFAs. Because of the high biological activity of tocopherols as antioxidants, they are uniquely successful in the protection of PUFAs in cell membranes. First, α-tocopherol reacts with the most prevalent free radical in membranes, the peroxy radical; second, it reacts rapidly and hence competitively. Free radicals in the cytosol are quenched by compounds soluble in this aqueous medium such as glutathione peroxidase, superoxide dismutase, and ascorbate. Some of these compounds also play an important role in regeneration of the tocopherol molecule after oxidation. Tocopherol, on reacting with a free radical, is converted to the tocopherol radical and is regenerated by ascorbate, glutathione, and possibly ubiquinone by reduction of the α-tocopheryl chromanoxy radical to tocopherol. The quantity of vitamin E required in the diet depends on the rate of production of free radicals, the PUFA composition of membranes (a function of diet), and other dietary compounds such as selenium (for synthesis of glutathione peroxidase) that are involved in protection from free-radical damage. Many of the PUFAs in the diet such as those from fish undergo peroxidation during processing and storage before ingestion. Therefore, it is not only the amount of PUFAs in the diet but also the degree of peroxidation that determines the vitamin E requirement.

Nonoxidant roles have also been proposed for vitamin E. These include modulation of prostaglandin synthesis, downregulation of protein kinase activity, and synthesis of xanthine oxidase. However, the prevention of free-radical damage and lipid peroxidation appears to be its major role.

Tocopherols occur mainly as free alcohols in plants, but many tocopherol-rich plant oils such as soybean oil have about half of the tocopherols as γ-tocopherol, which has a biological activity only 0.1 that of α–tocopherol. Since the majority of tocopherols in plants are not α-tocopherol, tocopherol mixtures isolated from plants are often methylated and referred to as "natural" α-tocopherol.

RRR-α-Tocopherol has the greatest biological activity of all the tocopherols, which suggests that the most favorable configuration of the phytyl side chain is *RRR*. Because non-α-tocopherol compounds have vitamin E activity, it is necessary to be able to express the total tocopherol activity of a mixture of tocopherols and tocotrienols. One tocopherol equivalent (TE) is equal to 1 mg of *RRR*-α-tocopherol. The other isomers are converted to TE by multiplying each milligram of isomer by the following relative activity factors: β-tocopherol, 0.5; γ-tocopherol, 0.1; α-tocotrienol, 0.3.

The relative values of various forms of tocopherol when expressed in IUs per mg relative to all-*rac*-α-tocopheryl acetate = 1 are all-*rac*-α-tocopherol = 1.10, *RRR*-α-tocopheryl acetate = 1.36; *RRR*-α-tocopherol = 1.49; all-*rac*-α-tocopheryl succinate = 0.89; and *RRR*-α-tocopheryl succinate = 1.21 (United States Pharmacopeia, 1985). These values were largely based on the prevention of fetal resorption by rats during gestation (Scott, 1978). Recent studies with humans, pigs, and guinea pigs in which the elevation of plasma concentrations was measured indicated that the biopotency of *RRR*-α-tocopherol compared to all-*rac*-α-tocopherol was closer to 2:1 than 1.36:1 (Acuff et al., 1994; Lauridsen et al., 2002; Hidiroglow et al., 2003). Use of this index of bioavailability has been challenged by Hoppe and Kennrich (2000) on the basis that it does not indicate a biological function. These authors suggest that rat bioassay values should be maintained. Table 8-1 lists vitamin E activities for various tocopherols in the prevention of fetal resorption and hemolysis in rats.

Biopotencies of the tocopherols have not been measured in dogs or cats. Traber et al. (1993) reported that vitamin E-replete and vitamin E-deficient dogs both preferentially increase the concentration of *RRR*-α-tocopherol over all *rac*-α-tocopherol in plasma when given both forms of the vitamin. Vitamin E deficiency apparently did not increase the apparent function of the hepatic tocopherol-binding protein, which is hypothesized to preferentially incorporate *RRR*-α-tocopherol into plasma.

The concentration of vitamin E in the diet necessary to protect against peroxidative deterioration of polyunsaturated phospholipids in cell membranes depends on the concentration of fat in the diet, the proportion of polyunsaturated fatty acids (Table 8-2), the degree of peroxidation of these fatty acids, the presence of other antioxidants, and the concentration of selenium. In many species, the requirement for vitamin E is inversely dependent on the selenium concentration and resulting activity of glutathione peroxidase. Although this interaction has not been demonstrated in dogs and cats, there is no reason to doubt its presence.

TABLE 8-1 Relative Vitamin E Activity of Various Tocopherols in Preventing Fetal Resorption and Hemolysis

Structure	Fetal Resorption	Hemolysis
RRR-α-Tocopherol	100	100
RRR-β-Tocopherol	25-50	15-27
RRR-γ Tocopherol	8-19	3-20
RRR-δ-Tocopherol	0.1-3	0.3-2
RRR-α-Tocotrienol	21-50	17-25
RRR-β- Tocotrienol	4-5	1-5
RRR-γ-Tocotrienol	—	—
RR-δ-Tocotrienol	—	—
RRR-α-Tocopheryl acetate	91	—
all-*rac*-α-Tocopherol[a]	74	—
all-*rac*-α-Tocopheryl acetate[a]	67	—

[a]Mixture of eight stereoisomers.
SOURCE: Chow, 2001.

TABLE 8-2 Estimated Minimal Requirement of Vitamin E Needed to Compensate for the Elevated Vitamin Demand Caused by Some Common Unsaturated Fatty Acids

Fatty Acid	Notation	Double Bonds	Vitamin E requirement (mg *RRR*-α-tocopherol·g^{-1} fatty acid)
Oleic	C18:1n-9	1	0.09
Linoleic	C18:2n-6	2	0.60
γ-Linolenic	C18:3n-6	3	0.90
α-Linolenic	C18:3n-3	3	0.90
Dihomo-γ-linolenic	C20:3n-6	3	0.90
Arachidonic	C20:4n-6	4	1.20
Eicosapentaenoic	C20:5n-3	5	1.50
Docosahexaenoic	C22:6n-3	6	1.80

SOURCE: Muggli, 1994.

Witting and Horwitt (1964) measured the time for onset of creatinuria in tocopherol-deficient rats given specially prepared fats of constant total unsaturation, but differing in composition with respect to PUFAs. They found that the relative quantities of tocopherol needed to protect 1 mol of mono-, di-, tri-, tetra, penta-, and hexaenoic acids were in the ratio of 0.3:2:3:4:5:6. These ratios are consistent with the observed rate of autooxidation of PUFAs in vitro, which increases according to the number of double bonds present (Cosgrove et al., 1987). Harris and Embree (1963) proposed a ratio between tocopherol in the diet (milligrams) and the PUFAs (grams) and suggested that this should be 0.6. For mixtures of PUFAs in the diet, Muggli (1994) proposed the formula:

$$M_{\text{vit E}} = 0.2 \times 10^{-3} (0.3m_1 + 2m_2 + 3m_3 + 4m_4 + 5m_5 + 6m_6),$$

where $M_{\text{vit E}}$ = moles of *RRR*-α-tocopherol and m_n = moles of unsaturated fatty acids with n double bonds.

When vitamin E is added to dog and cat foods as tocopherol (alcohol), recoveries following extrusion and drying are low and rate of loss on subsequent storage is high. With esters such as tocopheryl acetate, higher recoveries are obtained on extrusion and drying and storage losses are reduced. Many factors beside the form of the vitamin interact in determining its retention in petfoods. Among these are free-radical production, efficiency of the antioxidant system used, stability of the fat, and presence of free metal catalysts. These are discussed further at the end of this chapter.

Dogs

Signs of Deficiency

A wide range of clinical signs of vitamin E deficiency in dogs has been reported. These include degeneration of skeletal muscles associated with muscle weakness and reproductive failure in both males (degenerative changes of the testicular germinal epithelium leading to aspermia) and females (birth of weak and dead puppies). Retinal degeneration has been described in dogs given vitamin E-deficient diets (Hayes et al., 1970; Riis et al., 1981; Davidson et al., 1998). In addition to muscular weakness, Van Vleet (1975) reported subcutaneous edema, anorexia, depression, dyspnea, and eventual coma in vitamin E-deficient dogs. Microscopically these dogs exhibited extensive skeletal muscle degeneration and regeneration, focal endocardial necrosis in the ventricular myocardium, intestinal lipofuscinosis, and renal mineralization. No changes in nerve conduction velocities or histology were found in vitamin E-depleted dogs (Pillai et al., 1993). Pillai et al. (1992) compared four erythrocyte fragility tests as indicators of vitamin E deficiency in dogs. The dialuric acid hemolysis test was the most sensitive in vitro assay, and the osmotic fragility and detergent sensitivity tests did not change in response to vitamin E deficiency. In the dialuric acid hemolysis assay, 50 percent hemolysis occurred when plasma α-tocopherol concentration declined to 1.7 mg·L^{-1}. Plasma concentrations of α-tocopherol in dogs given a vitamin E-deficient diet follow a linear decline when expressed on a log concentration-time basis (Pillai et al., 1993).

Requirements

Many of the earlier studies of the vitamin E requirement of dogs preceded recognition of its interrelation with other antioxidant systems and the effect of the levels of PUFAs in the diet. A requirement for vitamin E in dogs was demonstrated by Anderson et al. (1939) who showed that muscular dystrophy in fox terrier puppies given a diet based on evaporated milk could be reversed by supplementation with *dl*-α-tocopherol. Using a similar basal diet, Elvehjem et al. (1944) demonstrated that 25 mg α-tocopherol per week (about 0.6 mg α-tocopherol·kg BW^{-1}·d^{-1}) did not support normal reproduction; 1 mg·kg BW^{-1}·d^{-1} supported reproduction, but one pup out of four from a bitch receiving this level developed mild muscular dystrophy.

Hayes et al. (1969) demonstrated that in the presence of large amounts of PUFAs in the diet, 100 mg α–tocopherol·kg^{-1} diet may be inadequate to prevent lipofuscin formation in dogs. Van Vleet (1975) gave four groups of beagle dogs a basal selenium and vitamin E-deficient diet (0.01 mg selenium and 1 mg α–tocopherol·kg^{-1} diet) based on dried Torula yeast and tocopherol-stripped lard. To the basal diet, either 30 mg α–tocopherol, 0.5 mg selenium, or 1 mg selenium was added per kilogram. Puppies given the basal diet alone developed progressive clinical signs of muscular weakness, anorexia, and elevated creatine phosphokinase and aspartate aminotransferase activities. No gross clinical signs occurred in supplemented dogs, but on necropsy the 0.5 mg selenium-supplemented dogs had mild skeletal myopathy. These observations with dogs are consistent with those in other species showing that in vitamin E-

selenium responsive diseases, supplementation of the diet with either selenium or vitamin E can ameliorate the clinical signs. Therefore, the requirement of vitamin E is conditional based on the selenium content of the diet.

Although no dietary requirement for ascorbic acid has been demonstrated in dogs, ascorbate is sometimes given to dogs under clinical conditions. High intakes of ascorbate have been shown to increase the vitamin E requirements of rats (Chen, 1981), indicating that caution should be exercised in the amount of ascorbate given to dogs.

The NRC (1985) suggested an allowance for growing puppies of 22 IUs of vitamin E·kg^{-1} diet supplying 3.67 kcal·g^{-1} (24 IUs per 4,000 kcal) and containing not more than 1 percent linoleic acid and at least 0.2 ppm of selenium. In the absence of data to the contrary, it is suggested that this value be maintained as an AI for growing puppies, adult dogs at maintenance, and pregnant and lactating bitches. To allow for the use of higher levels of PUFAs in the diet, it is suggested that a ratio of α–tocopherol (milligrams) to PUFAs (grams) of at least 0.6 be maintained.

Hypervitaminosis

High doses of vitamin E given to several species of animals have been shown to be relatively nontoxic. However, there are reports of extreme intakes interfering with the absorption or metabolism of vitamins D and K. There is no information on vitamin E toxicity in dogs. Hall et al. (2003) gave dogs 447 mg all-*rac*-tocopheryl acetate for 17 weeks and reported no adverse effects. The NRC (1987) suggested a maximum tolerable level in the range of 1,000 to 2,000 IU·kg^{-1} diet and a tentative use level of 75 IU·kg BW^{-1}·d^{-1}.

Cats

Signs of Deficiency

Vitamin E deficiency in cats has been associated with depression and anorexia, hyperesthesia on palpation of the ventral abdomen, and nodular adipose tissue. On gross pathology, enlargement of the spleen and orange or orange-tan colored adipose tissue (Cordy, 1954; Coffin and Holzworth, 1954) were the most significant findings. Microscopic examination of the adipose tissue revealed foci of steatitis, neutrophilic infiltration, and accumulation of ceroid pigment as globules and as peripheral rings in the adipocytes. The ceroid pigment is acid-fast and insoluble in fat. Interstitial myocarditis, focal myositis of skeletal muscles, periportal mononuclear infiltration of the liver, and steatitis were also reported (Gershoff and Norkin, 1962).

Requirements

Because of the nature of the diets consumed by cats, they are more susceptible than dogs to vitamin E deficiency. Cat diets, especially canned, are typically higher in fat than dog diets and are frequently based on fish products, especially tuna, containing long-chain PUFAs that are prone to lipid peroxidation. Cordy (1954) reported that 20 or 40 mg of all-*rac*-α-tocopherol per day protected kittens given a commercial cat food composed mainly of fish from the development of steatitis, whereas 10 mg of all-*rac*-α–tocopherol was inadequate. Gershoff and Norkin (1962) gave kittens a basal purified diet containing 200 g·kg^{-1} of vitamin E-free lard without vitamin E supplementation. Steatitis was not observed in any of the kittens receiving this basal diet, even in the absence of vitamin E. However, on histological examination, four of the six kittens were found to have focal myositis of the skeletal muscles and myocarditis. Supplementation of the basal diet with 17 IUs of *d*-α-tocopherol·kg^{-1} decreased the incidence of myositis to one cat in four, whereas addition of 34 or 68 IUs of vitamin E·kg^{-1} prevented lesions in all cats. When 50 g of tuna oil was substituted for lard in the diet, cats without vitamin E supplementation developed severe steatitis. When 34 IUs of vitamin E·kg^{-1} were added to the tuna oil-supplemented diet, the severity of steatitis was diminished and it was totally absent when 136 IUs of vitamin E were added to the tuna oil diet.

Because of the demonstrated relationship between vitamin E requirement and quantity of PUFAs in the diet, it is infeasible to give a single minimal value that will be adequate for all diets. The NRC (1986) suggested 30 mg of α–tocopherol·kg^{-1} for a diet relatively low in fat (<10 percent of the dry weight) containing antioxidants and an adequate level of selenium (0.12 mg selenium·kg^{-1} diet). This concentration represents 6 mg per 1,000 kcal and is proposed as an adequate intake. High-PUFA diets, especially those containing fish oils subject to peroxidation, may require four or more times this level for the prevention of steatitis. In the absence of definitive information, an allowance of 24 mg α-tocopherol·kg^{-1} diet is recommended for low-fat (<10 percent) diets and 120 mg·kg^{-1} for diets with a high concentration of PUFAS. A ratio of at least 0.6 mg of tocopherol per gram of PUFA in the diet should be maintained.

Hypervitaminosis

While vitamin E is generally regarded as one of the least toxic fat-soluble vitamins, excessive intake in chickens and rats has produced effects that appear antagonistic to the functions of vitamins D and K. Intakes of 2,200 IU of all-*rac*-α-tocopheryl acetate·kg^{-1} diet have been associated with growth depression, increased prothrombin time, and depressed bone calcification when chickens were given calcium- or vitamin D-deficient diets (March et al., 1973). Phelps (1981) gave kittens from birth to 3 weeks of age intramuscular or subcutaneous injections of *dl*-α-tocopherol (E-alcohol) or *dl*-α-tocopheryl acetate (E-acetate) equivalent to about 50 to 1,000 mg·kg BW^{-1}·d^{-1}. Toxicity was dose related, no mortality occurred at 5 mg of vitamin E-alcohol

per day (approximate 20 $mg \cdot kg^{-1} \cdot d^{-1}$), but significant mortality occurred at doses equivalent to 100 to 200 $mg \cdot kg^{-1} \cdot d^{-1}$. A dose of 1,000 mg of vitamin E-alcohol$\cdot kg^{-1} \cdot d^{-1}$ caused death in all kittens.

Cats given salmon- and tuna-based diets fortified with vitamin E exhibited prolonged clotting time, which was restored by vitamin K therapy (Strieker et al., 1996). The data do not allow for a safe upper limit of vitamin E to be defined.

VITAMIN K

The term vitamin K is a generic descriptor of 2-methyl-1,4-napthoquinone and all derivatives of this compound that exhibit antihemorrhagic activity in animals fed a vitamin K-deficient diet (Suttie, 2001). The naturally occurring compound 2-methyl-3-phytyl-1,4-napthoquinone, which is widely distributed in plants (especially leaves) and frequently designated vitamin K_1, is preferentially called phylloquinone. The compound originally isolated from putrefied fish meal and called vitamin K_2, which is one of a series of vitamin K compounds with unsaturated side chains, called multiprenyl menaquinones, is found in animal tissue and bacteria. Vitamin K_2 is the term used to encompass a series of menaquinones having between 4 and 13 prenyl groups.

The parent compound of the vitamin K series is 2-methyl-1,4-napthoquinone, known as menadione. This compound was previously known as vitamin K_3, but it does not have biological activity until a side chain is added either by microorganisms in the gut or by tissue alkylating enzymes. Plants and bacteria synthesize the napthoquinone ring structure from shikimic acid, but animals cannot; so, this portion of the vitamin has to be provided in the diet or be synthesized by intestinal microbes. For many species, intestinal synthesis meets the total requirement.

Absorption, Metabolism, and Excretion

Absorption of phylloquinones from the gut requires incorporation into micelles whose formation is facilitated by the presence of bile salts and pancreatic secretions. The efficiency of absorption of vitamin K from foods has not been studied in either dogs or cats but has been shown in other species to be variable and to depend on the food source. Defective fat absorption reduces the uptake of vitamin K from the gut, and animals with steatorrhea and persistent diarrhea are likely to have poor absorption. Once the micelle is taken up by the enterocyte, it passes into the lymphatic system and is transported by chylomicrons and other LDLs in the plasma. In rats, the liver is the main site of storage of phylloquinones; about half of a 10-μg dose was found in the liver after 3 hours. However, the half-life of phylloquinone in rat liver is only 10-15 hours; so, liver concentration is highly dependent on recent absorption.

Synthetic menadione may be absorbed from both the small intestine and the colon by a passive process. Absorption of menadione in chicks is dependent on the presence of lipid in the diet. The water-soluble form, menadione sodium bisulfite, which is more stable than menadione, is used commercially in some dog and cat foods. While menadione is not biologically active, it is alkylated to biologically active menaquinones either by microorganisms in the gut or by the tissues of the animals. Studies with 2-methyl-1, 4-naphthoquinone substituted at the 3-position have shown that polyisoprenoid side chain substitutes are the most effective.

The metabolism of phylloquinones has not been studied in either dogs or cats, but, in humans, 40 to 50 percent of the radioactivity from a dose of phylloquinone appeared in feces and 20 percent in urine (Shearer et al., 1974). Menadione is metabolized and excreted rapidly, and only a minor portion of this synthetic form of the vitamin is converted to biologically active menaquinone-4 (MK-4). When anticoagulant therapy is given, the disappearance of radiolabeled vitamin K from plasma is not markedly altered, but there is greatly increased urinary excretion and decreased fecal excretion of the radiolabeled vitamin K.

Biological Function

The unique function of vitamin K is to facilitate carboxylation of the glutamic acid residues of proteins that require this for activation. These proteins form three groups: vitamin K-dependent clotting factors, vitamin K-dependent skeletal proteins, and other vitamin K-dependent proteins. The vitamin K-dependent step in prothrombin synthesis results in the uptake and fixation of CO_2 in γ-carboxyglutamic acid residues in the fragment 1 region of prothrombin. The reaction takes place on the luminal side of the rough endoplasmic reticulum of the microsomal fraction of liver, which is rich in carboxylases. Suttie (2001) proposed the following mechanism for the reaction. Oxygen interacts with the reduced form of vitamin K, forming an oxygenated intermediate, which is sufficiently basic to abstract the γ-hydrogen of the glutamyl residue. The product of this reaction would be vitamin K epoxide and a glutamyl carbanion. ATP is not required for this reaction, and the energy needed appears to come from the oxidation of reduced vitamin K.

The second group of proteins that requires vitamin K for their function is associated with bone, of which the first isolated was named bone Gla protein or osteocalcin. This protein is synthesized in bone, and small amounts circulate in the plasma. Higher levels occur in the plasma of children than adults, and the level in plasma has been used as an indicator of bone formation. Osteocalcin from cats has been sequenced (Shimomura et al., 1984), and an antibody to cat osteocalcin was used by Morris and Earle (1999) to deter-

mine concentrations in the plasma of kittens. Two similar proteins have been isolated from bone, matrix Gla protein and protein S. The third group of Gla-containing proteins comes from various tissues and has not been extensively studied.

Anticoagulants of the 4-hydroxycoumarin class are effective antithrombotic drugs and are also used as rodenticides. When warfarin is administered to animals, there is an increase in the 2,3-epoxide of vitamin K, which was thought to inhibit normal recycling of the vitamin. It is now thought that warfarin inhibits the recycling of vitamin K to its enzymatically active form and therefore limits the action of the carboxylases (Suttie, 2001).

Phylloquinones are not generally used to supplement petfoods because of their cost. The stability of menadione from petfoods after extrusion, drying, and enrobing is low; so, the following menadione derivatives (in order of increasing recovery) are used: menadione sodium bisulfite, menadione sodium bisulfite complex, menadione dimethylpyrimidinol bisulfite, and menadione nicotinamide bisulfite.

Dogs

Signs of Deficiency

Naturally occurring vitamin K deficiency in the absence of anticoagulants has not been reported in normal dogs. Deficiencies may occur secondary to chronic liver disease and prolonged cholestasis and result in a prolongation of clotting times and excessive bleeding. Accidental ingestion by dogs of rodenticides containing analogues of dicumarol as anticoagulants has resulted in a decrease in prothrombin times to 10 percent of normal (Clark and Halliwell, 1963).

Requirements

The dietary requirement for vitamin K depends on the extent of intestinal synthesis, the efficiency of absorption, and the presence of antagonistic factors such as dicumarols. Determination of a requirement is complicated by the insensitivity of the prothrombin time assay. Anderson and Barnhart (1964) demonstrated the metabolic need of dogs for vitamin K for prothrombin synthesis. By the use of fluorescent antibodies, they showed that prothrombin was synthesized only in the parenchymal cells of the liver. In normal dogs, there was a cyclic activity of these cells, which is markedly asynchronous, and only 10 to 20 percent of the parenchymal cells contain significant amounts of prothrombin. All parenchymal cells could be synchronized to produce prothrombin by treatment with vitamin K_1. In dogs rendered prothrombin-deficient by treatment with dicumarol, synthesis of prothrombin could be visualized in the parenchymal cells within 1 hour after administration of vitamin K_1, and by 4 hours at least 80 percent of the parenchymal cells were fluorescent. In these dogs, prothrombin times also returned to control levels within 4-6 hours.

Quick et al. (1962) induced vitamin K deficiency in puppies by cholecystonephrostomy (diversion of the bile into the pelvis of the kidney) and determined the intravenous vitamin K_1 requirement to maintain normal prothrombin time. For growing puppies, this varied between 5 and 15 $\mu g \cdot kg\ BW^{-1} \cdot d^{-1}$. In dogs that had reached weight maintenance, the requirement was 2 to 5 $\mu g \cdot kg\ BW^{-1} \cdot d^{-1}$.

There are a number of reports of accidental ingestion by dogs of rodenticides containing vitamin K antagonists. In a controlled study, Clark and Halliwell (1963) administered 2.2 mg of warfarin (a synthetic analogue of dicumarol)·kg BW^{-1} to adult dogs daily for 3 days, which reduced prothrombin times to 10 percent of normal. Prothrombin times could be restored to 70 percent of normal within 4 hours with an intravenous dose of 2.2 or 4.4 mg vitamin $K_1 \cdot kg\ BW^{-1}$, but doses had to be repeated to maintain prothrombin levels. Lower doses gave a lower response in prothrombin values, and intramuscular administration gave a more prolonged response. Intravenous administration of menadione phosphate did not produce a response and is unsuited for this route of administration because it results in hemolysis. Bratt et al. (1965) reported suspected vitamin K deficiency in newborn puppies, but they did not report any measurement of clotting times or factors nor did they have any controls.

Many commercial dog foods do not contain supplemental vitamin K, and there is a lack of reports of dogs fed these diets having prolonged clotting times. Whether there is a need for supplemental vitamin K in the absence of compounds that interfere with bacterial synthesis and absorption of the vitamin or vitamin K antagonists is not known. However, as a precaution the NRC (1985) suggested that 22 μg menadione·kg $BW^{-1} \cdot d^{-1}$ be added to diets of adult dogs and 44 μg menadione·kg $BW^{-1} \cdot d^{-1}$ to diets of growing puppies. These would be more than supplied by a dietary concentration of 0.97 and 1.32 mg menadione·kg^{-1} (4 kcal·g^{-1}) for growing puppies and adult dogs at maintenance respectively. No recommendations were given for pregnant and lactating bitches. For diets suspected of providing inadequate intestinal synthesis of vitamin K, 1.3 mg menadione·kg^{-1} (4 kcal·g^{-1}) is suggested.

Hypervitaminosis

No studies of vitamin K excess have been made in dogs. The naturally occurring phylloquinones have not been shown to be toxic to any species by any route of administration. The toxic level of menadione in the diet is at least 1,000 times the dietary requirement (NRC, 1987). Menadione should not be administered by the parenteral route because it is toxic in doses from a few hundred milligrams per kilogram of body weight to as low as 2 to 8 mg·kg BW^{-1} in horses (NRC, 1987).

Cats

Signs of Deficiency

Prolonged clotting times have been recorded in cats that have accidentally ingested dicumarol-based rodenticides. A number of clinical conditions such as hepatic lipidosis, inflammatory bowel disease, cholangiohepatitis, and enteritis result in malabsorption of lipids and induce a secondary deficiency of vitamin K. These conditions are generally associated with an increase in proteins involved with vitamin K absence (PIVKAs) and respond to vitamin K therapy (Edwards and Russell, 1987; Center et al., 2000).

A congenital deficiency of all vitamin K-dependent blood coagulation factors has been reported in the Devon Rex breed of cats (Maddison et al., 1990; Soute et al., 1992; Littlewood et al., 1995). Soute et al. (1992) demonstrated that this coagulation abnormality was accompanied by a defective γ-glutamyl carboxylase.

Cats, like other higher animals, have a metabolic requirement for vitamin K to carboxylate glutamyl residues in specific proteins. Strieker et al. (1996) attempted to produce vitamin K deficiency in kittens by giving purified diets with various additions to simulate commercial diets based on fish that had resulted in prolonged clotting times. The additions included antibiotics, salmon oil, high levels of herring oil, high levels of α-tocopherol, and retinyl palmitate, but neither the purified diet alone nor the diet with additional compounds increased clotting times. One of the purified diets contained 4 μg of vitamin $K_1 \cdot kg^{-1}$.

Diminished factor VII activity has been reported in cats with liver disease (Lisciandro et al., 1998). Center et al. (2000) found that 21 of 24 cats that had abnormal PIVKA tests responded to parenteral vitamin K therapy. Of these 21 cats, seven had hepatic lipidosis, four had severe inflammatory bowel disease, and five had cholangiohepatitis.

Requirements

Many commercial cat foods do not contain supplemental vitamin K, relying on the contribution of the dietary ingredients and intestinal synthesis. Since there have been no reports of diets (except those containing significant amounts of fish) in which vitamin K supplementation is indicated, it appears that supplementation is not generally required. Strieker et al. (1996) reported clinical signs of vitamin K deficiency in cats receiving two commercial canned diets high in salmon or tuna in protocol tests. Several of the queens and kittens given these diets died of hemorrhages, and the surviving cats had prolonged clotting times that responded to vitamin K_1. These fish diets contained 60 μg vitamin $K \cdot kg^{-1}$, which was insufficient to provide the vitamin K need of cats under these conditions. The vitamin K requirement of cats given diets that do not contain fish may be met by microbial synthesis in the intestine. Cats given fish-based diets may require supplemental vitamin K in addition to that provided by microbial synthesis in the gut. Diets containing a high proportion of fish should have menadione added. There is no information available on the amount of vitamin K required in these diets. A dietary allowance of 1.0 mg menadione$\cdot kg^{-1}$ (4 kcal$\cdot g^{-1}$) is suggested as an adequate intake.

Hypervitaminosis

Phylloquinone, the natural form of vitamin K has not shown toxic effects when administered to animals by any route (NRC, 1987). The toxic level of menadione in the diet is at least 1,000 times the dietary requirement of animals other than cats. Menadione should not be given by the parenteral route because it causes hemolysis and toxicity in low doses.

THIAMIN (VITAMIN B_1)

Thiamin was the first of the water-soluble vitamins to be isolated and was given the trivial name vitamin B_1. Thiamin is not synthesized in the tissues of cats and dogs but is synthesized de novo by some microorganisms and plants. Some microbes synthesize thiamin only when the pyrimidine and thiazole moieties are present.

Although thiamin occurs widely in foods of both animal and plant origin, it is abundant in only a few. Rich sources of thiamin are yeast, wheat germ, kidney, liver, and legume seeds. In cereals, the concentration of thiamin is highest in the germinal portion of the grain and lowest in the endosperm. Most of the thiamin in plants is present in nonphosphorylated forms, whereas in animal tissue it is mostly (80-85 percent) present as thiamin pyrophosphate (TPP), with lesser amounts of the monophosphate (TMP) and triphosphate (TTP) (Tanphaichitr, 2001). Nonphosphorylated forms of thiamin in animal tissues are only 2 to 5 percent of total thiamin.

Foods may contain compounds that have antithiamin properties (known as thiaminases), which are heat labile. Thiaminases are present mainly in the viscera of some freshwater fish and in a limited number of marine fish and certain bacteria. Thiaminases of fish and some bacteria are classified as thiaminase I and catalyze a nucleophilic displacement of the methylene group of the pyrimidine moiety of thiamin. Carp and saltwater herring contain thiaminases, but perch, catfish, butterfish, and spots apparently do not (Smith and Proutt, 1944). The other heat-labile thiaminase (thiaminase II) is present in some bacteria and catalyzes the hydrolysis of thiamin. Both thiaminase I and thiaminase II are inactivated by cooking.

The other class of antithiamin compounds is heat stable, and includes the ortho and para polyphenolics such as tannins. These compounds are not generally included in significant amounts in dog and cat diets and are of little concern.

Thiamin is quite stable to heat and oxidation when the pH is below 5. Above this pH, inactivation of thiamin is accelerated by increasing pH and heat. In strongly alkaline solutions, thiamin is oxidized to thiochrome, which is fluorescent and used in the analytical determination of thiamin. In the heat processing of dog and cat foods, large losses of thiamin can occur. Canned foods often contain gelling agents that increase the pH of the food and in combination with prolonged heat during retorting result in extensive inactivation of thiamin.

Sulfites, which are often used for food preservation, cleave the thiamin molecule at the methylene bridge, and thiamin deficiency associated with the feeding of meat preserved by sulfur dioxide has been reported in cats and dogs (Studdert and Labuc, 1991).

Cats are more susceptible to thiamin deficiency than dogs because they require about four times as much thiamin in the diet. Also, fish-based diets that contain active thiaminases before processing can destroy thiamin added to these diets and frequently are given to cats, but rarely to dogs. These factors may account for persistence of reports of thiamin deficiency in cats fed commercial foods (Davidson, 1992).

Absorption

Thiamin is absorbed from the small intestine mainly in the jejunum and ileum by both an active and a passive process. Active absorption occurs at concentrations less than 2 μM, requires Na^+, and is inhibited by ouabain, which blocks ATPase, and implicates a specific thiamin transporter. At thiamin concentrations greater than 2 μM, there is passive absorption. Most of the thiamin in mucosal cells is phosphorylated, but, on passage through the cells and appearance at the serosal side, it is dephosphorylated and appears as free thiamin in the plasma. In humans, 20-30 percent of the thiamin in plasma is protein bound and taken into erythrocytes by a facilitated diffusion process and into other cells by active transport. In these cells, about 80 percent of thiamin is present as TPP, 10 percent as TTP, and the remainder as TMP and thiamin. Thiamin pyrophosphokinase catalyzes the phosporylation of free thiamin to TPP, which in turn may be phosphorylated to TTP by phosphoryltransferase.

A large number of metabolites of thiamin have been identified in urine, which is the main route of excretion; very little appears in the feces.

Biological Function

TPP is the major coenzymatic form of thiamin, and its synthesis from thiamin involves Mg^{2+} and ATP, and is catalyzed by thiamin pyrophosphate kinase. The substituted pyrimidyl portion of the molecule is involved in apoenzyme recognition and binding, and the thiazole moiety contains the reactive center. TPP is a coenzyme in two types of active aldehyde transfer reactions: oxidative decarboxylation of α-ketoacids (such as pyruvate and α-ketoglutarate) and branched-chain α-keto acids, and transformation of α-ketols (transketolase reaction). In these reactions, the carbon between the nitrogen and sulfur of the thiazole ring ionizes and readily adds to carbonyl groups of α-ketoacids, which results in loss of CO_2. These reactions have particular significance in energy and carbohydrate metabolism. A number of nonenzymatic functions have been proposed for thiamin especially in neural tissue. In these functions, such as activation of ion channels, thiamin is involved as TPP.

The measurement of erythrocyte transketolase stimulation by TPP has been used in the diagnosis of thiamin deficiency in cats and dogs (Brin and Vincent, 1965; Noel et al., 1971; Deady et al., 1981a,b; Read and Harrington, 1982; Grimm et al., 1988). However, a decrease in concentration of TPP in the blood of rats precedes a change in erythrocyte transketolase activity (ETKA) (Warnock et al., 1978). Thiamin and its phosphorylated esters may be measured by high-performance liquid chromatography (HPLC; Ishii et al., 1979; Lynch et al., 1997). The plasma must be treated with a phosphatase to obtain total thiamin concentration. Most methods use ultraviolet or fluorescence detection, the latter requiring either pre-column or post-column oxidation of thiamin to thiochrome (Lynch and Young, 2000). The HPLC method is precise and yields results that correlate well with ETKA (Talwar et al., 2000).

Dogs

Signs of Deficiency

Because of the body's limited storage of thiamin, clinical signs of deficiency appear in a shorter time after exposure to a thiamin-deficient diet than for most other vitamins. Clinical signs of thiamin deficiency were induced by Read and Harrington (1981) who gave 2- to 5-month-old beagle puppies a thiamin-deficient diet (20 to 30 μg thiamin·kg^{-1}). These authors reported three stages of the disease: an initial short (18 ± 8 days) induction period in which the dogs appeared healthy but grew slowly, followed by an intermediate stage of variable duration (59 ± 37 days) of inappetence, failure to grow, body weight loss, and coprophagia. This was followed by a terminal period (8 ± 6 days) of neurological involvement or sudden death. Neurological abnormalities included central nervous system depression, sensory ataxia, paraparesis, torticollis, circling, tonic-clonic convulsions, profound muscular weakness, and recumbency. In these deficient dogs ETKA was depressed.

The most consistent pathological lesions of thiamin deficiency involve the nervous system and heart. Acute thiamin deficiencies tend to involve the brain and produce severe neurological signs, whereas chronic deficiencies produce pathological changes of the myocardium and peripheral

nerves (Read, 1979). Lesions in the brain include symmetrical necrosis of the gray matter of the inferior colliculi, medial vestibular nuclei, cerebellar nodulus, claustra, and cerebral cortex (Read et al., 1977; Read, 1979). Read and Harrington (1986) described changes in the central nervous system of thiamin-deficient dogs. They described two topographical patterns in the brain: one involved only the caudal colliculi, while the other involved the suprasplenial gyri of the caudal cortex and the claustra, caudal colliculi, cerebellar nodulus, and medial vestibular nuclei. The gray matter was primarily involved, and in bilateral structures the two sides were equally affected. Histological changes associated with peripheral neuropathy include diffuse bilateral myelin degeneration and axonal disintegration (Voegtlin and Lake, 1919; Street et al., 1941; Read, 1979). Thiamin deficiency did not affect the rate of hemoglobin regeneration in dogs subjected to periodic phlebotomy (Maas et al., 1944).

Requirements

One of the earliest observations of thiamin deficiency in dogs was made by Andrews (1912), who found that young puppies nursed by mothers whose infants had died of beriberi developed polyneuritis. Voegtlin and Lake (1919) described polyneuritis in dogs given a diet of meat made alkaline with sodium carbonate and cooked for 3 hours at 120°C. Clinical signs of thiamin deficiency became apparent after dogs received the diet for 1 month to 6 weeks. These authors reported that the dogs became anorectic and lost body weight, had tonic convulsions that gave way to progressive paralysis of the legs and an inability to walk, exhibited hypothermia, and died within a few days of the initial paralysis. Cowgill (1921) used a purified diet based on casein as the protein source, which produced polyneuritis in dogs that could be reversed with various alcoholic extracts of wheat embryos, rice polishings, and navy beans. Subsequently, Cowgill (1934) reported that a daily intake of 6 μg of thiamin·kg BW^{-1}·d^{-1} was adequate for the maintenance of mature dogs. Somewhat higher levels of 8 μg·kg BW^{-1}·d^{-1} were suggested for adult dogs (6 to 10 kg BW) by Street et al. (1941) based on the apparent good health of dogs given a 25 percent fat diet and either 6.7 or 9.4 μg of thiamin·kg BW^{-1}. Intakes of 1.8 to 2.3 μg·kg BW^{-1} would keep an animal alive. Most of the diets used by early workers to determine thiamin requirements were based on autoclaved dietary constituents to provide all B vitamins other than thiamin. These diets often had multiple vitamin deficiencies; for example, the dogs given the diet of Cowgill (1921) developed foul breath, which is a clinical sign of niacin, not thiamin, deficiency in dogs. Even the later diets of Arnold and Elvehjem (1939b) and Street et al. (1941) used autoclaved yeast. Maas et al. (1944) used a purified diet fortified with isolated B vitamins and reported that less than 10 μg·kg BW^{-1} was inadequate for weight maintenance in adult dogs.

For maintenance of food intake and growth of puppies, Arnold and Elvehjem (1939b) reported that a concentration of 500 μg thiamin·kg^{-1} of nonfat constituents in the diet was inadequate and estimated that 750 μg thiamin hydrochloride·kg^{-1} diet was required to maintain food intake and growth in puppies fed a low-fat diet. For a diet containing 56 percent "fat," the requirement was about one-third of that amount. The authors stated that their results "warrant the conclusion that the thiamin requirement is best stated as a percentage of the diet" (rather than on a body weight basis).

In animals other than dogs, inclusion of oral antibiotics, lactose, sorbitol, and ascorbic acid in the diet increases the thiamin requirement (Evans and Lepkovsky, 1928, 1929, 1935; Scott and Griffith, 1957; Haenel et al., 1959). Factors affecting microbial synthesis of thiamin in the gut and the degree of coprophagy practiced may also influence the requirement.

Noel et al. (1971) gave four groups of growing beagle puppies a purified diet fortified with B vitamins other than thiamin. Groups of dogs were given one of four levels of thiamin (per kg BW^{-1}): 110, 33, or 22 μg daily or 115 μg twice weekly. Dogs were maintained on the diet for 29 weeks, but the dose rate for the 110-μg group was reduced to 11 μg·kg^{-1} and the 115-μg twice weekly group was reduced to 77 μg for the last 8 weeks. One dog in the 22-μg·kg BW^{-1} group began to lose weight at 9 weeks, had transitory diarrhea and anorexia, and died at 22 weeks. The ETKA test (Brin and Vincent, 1965) indicated that the dog was deficient in thiamin. The authors concluded that 22 μg thiamin·kg BW^{-1}·d^{-1} was inadequate for beagles in the first year of life.

There have been no additional studies of the thiamin requirement of dogs since the last revision of the NRC (1985) report. Therefore, it is proposed that the dietary concentration of 270 μg thiamin per 1,000 kcal ME (1.08 mg·kg^{-1} diet of 4 kcal·g^{-1}) for growing dogs be maintained. This concentration is equivalent to 75 μg thiamin·kg $BW^{-0.75}$·d^{-1} for growth. Since Noel et al. (1971) demonstrated that 22 μg of thiamin·kg BW^{-1}·d^{-1} was inadequate for 22-week-old beagle dogs, it is proposed that the requirement for maintenance be increased to 30 μg·kg BW^{-1}·d^{-1}, which is equivalent to a dietary concentration of 450 μg per 1,000 kcal for a 15-kg dog. It is of interest that the dietary concentration of thiamin needed for maintenance is greater than that proposed for growth. No information is available regarding the requirements for pregnancy and lactation, but it is proposed that the allowance for maintenance of 450 μg per 1,000 kcal be used.

It should be noted that these amounts and concentrations are at the point of ingestion. Considerably higher concentrations may be required in foods to allow for destruction resulting from thermal processing, storage losses, and antithiamin agents. ABGE (1989) recommended daily allowances of 20 μg thiamin·kg BW^{-1} for maintenance and 55 μg thiamin·kg BW^{-1} for growth and reproduction.

Hypervitaminosis

Studies on laboratory animals, including dogs, indicate that the parenteral administration of thiamin hydrochloride may be the only route by which signs of thiamin toxicity can be produced (NRC, 1987). There are no reports of toxicity resulting from oral ingestion of thiamin by dogs. Rapid intravenous injection of 5 to 50 mg thiamin·kg BW^{-1} produced transient fall in blood pressure, and higher doses resulted in more severe effects. The lethal dose is approximately 350 mg·kg BW^{-1} (Neal and Sauberlich, 1980). No adverse effects were observed in dogs given daily oral doses of 100 μg thiamin·kg BW^{-1} (Noel et al., 1971). However, this amount is only about three times the requirement. If the general recommendation of the NRC (1987) of 1,000 times the requirement for puppies is taken, this would be equivalent to a concentration of 1.08 g thiamin·kg^{-1} diet for a growing dog. For rats, the median lethal dose (LD_{50}) for oral thiamin is 6 g·kg BW^{-1}, but for subcutaneously administered thiamin it is 500 mg·kg BW^{-1} (Molitor, 1942). The maximum safe upper limit of thiamin in the diet of dogs has not been defined.

Cats

Signs of Deficiency

Three stages of thiamin deficiency in cats were described by Everett (1944). The first stage was characterized by anorexia; the second stage, by the appearance of neurological signs including those involving posture and short tonic convulsive seizures; and the third or terminal stage, by progressive weakness, prostration, and death. The first or anorectic stage frequently occurred within 1 to 2 weeks of consumption of a deficient diet and may be accompanied by emesis (Jubb et al., 1956; Deady et al., 1981). In the second stage, there was impairment of labyrinthine righting reflexes, as shown by ventroflexion of the head, loss of righting reflex, and defective conscious proprioception. Affected cats when suspended by their hind legs kept their heads ventroflexed instead of dorsoflexed. Ventroflexion of the head caused cats to somersault when they jumped from a table to the floor (Jubb et al., 1956; Loew et al., 1970). Impaired vestibulolocular reflexes included decreased nystagmus time and an impaired or slow papillary light reflex. Affected kittens often had mydriasis, were ataxic, and held their tails erect.

Toman et al. (1945) reported that electrocardiographic changes, including sinus bradycardia, occurred in thiamin-deficient cats as early as the second week of a deficient diet. Thiamin therapy resulted in a prompt correction of heart rate disorders, but changes in the ventricular complex (QRS prolongation and other changes, and T wave) were slower to respond. When thiamin-deficient cats exhibit spontaneous seizures they may be accompanied by brief periods of tachycardia followed by severe bradycardia.

Thiamin deficiency induces pathological changes in the central nervous system, which include symmetrical hemorrhages in the periventricular gray matter in severe cases. Considerable variation in the number of nuclear masses involved has been reported, but the main nuclei involved in order of frequency were inferior colliculi, medial vestibular, lateral geniculate, habenular and occulomotor nuclei in the accessory vestibular, and cuneate and red nuclei (Jubb et al., 1956; Deady et al., 1981a,b). Thiamin deficiency induced by a thiamin-deficient diet or the antagonist pyrithiamin resulted in severe learning deficits in cats (Irle and Markowitsch, 1982).

Requirements

When cats were given a diet of autoclaved dog food supplemented with riboflavin, pyridoxine, and calcium pantothenate, Everett (1944) found that daily injections of 0.5 mg thiamin prevented neurological disorders and allowed weight maintenance or gain in adults. Loew et al. (1970) estimated that the daily thiamin requirement of adult cats for maintenance was about 0.36 mg for a 3-kg cat, equivalent to about 2 mg thiamin per 1,000 kcal ME. Deady et al. (1981a) gave kittens purified amino acid-based diets that contained 4.4 mg added thiamin·kg^{-1} diet. When a diet containing 90 g of glutamic acid was followed by a similar diet that contained 120 g glutamic acid·kg^{-1} (or vice versa), kittens developed severe neurological signs of thiamin deficiency that responded to parenteral thiamin.

Several attempts (Carvalho Da Silva et al., 1961; Partington et al., 1964) have been made to determine the thiamin requirements of cats by urinary excretion of thiamin or thiochrome. Cat urine contains substances that interfere with fluorescent measurement of thiochrome.

Purified diets containing 5 mg thiamin·kg^{-1} have been adequate for kitten growth and for pregnancy and lactation (J. G. Morris and Q. R. Rogers, University of California, Davis, personal communication).

The above studies suggested a dietary thiamin concentration of 5 mg·kg^{-1} diet (approximately 4.7 kcal·g^{-1}) for growth of kittens. As the requirement is linked to energy metabolism, it is suggested that this requirement be extended to apply to diets formulated for maintenance, pregnancy, and lactation. The requirements may increase when cats are given diets with a small proportion of the energy contributed by fat.

Hypervitaminosis

There are no reports of toxicity resulting from excessive oral intakes of thiamin, but intravenous thiamin in high doses can cause neuromuscular and ganglionic blockade (Freye and Agoutin, 1978). A SUL of thiamin in the diet of animals suggested by the NRC (1987) was 1,000 times the dietary requirement. For cats this would be approximately 5 g thi-

amin·kg^{-1} diet. For most laboratory animals, the toxic level of thiamin by parenteral administration is in the approximate range of 80 to 400 mg·kg BW^{-1}. The safe upper conenctration of thiamin in the diets of cats has not been defined.

RIBOFLAVIN

Most of the riboflavin in foods occurs in the coenzyme form of flavin mononucleotide (FMN), as flavin adenine dinucleotide (FAD), or as flavins covalently bound to proteins generally at the 8-α-methyl position of the isoalloxazine ring. Milk is an exception in that a high percentage of the riboflavin is free and not bound. Animal products tend to be good sources of riboflavin, whereas grains are not. Most food sources high in riboflavin are high in the other vitamins of the B complex. A deficiency of riboflavin in the diet impacts other vitamins because flavin coenzymes are involved in their metabolism. These vitamins include folic acid, pyridoxine, niacin, and vitamins K and D.

Riboflavin and its coenzymes are sensitive to alkaline and acid conditions particularly in the presence of UV light. Under acid conditions, riboflavin is degraded to lumichrome, which is biologically inactive, and under alkaline conditions to lumiflavin, which is also biologically inactive.

Absorption

In foods, most riboflavin is in the coenzyme form, which requires that it be hydrolyzed in the gut prior to absorption. Flavins are absorbed in the upper gastrointestinal tract by specialized transport involved in dephosphorylation-rephosphorylation mechanisms rather than by passive diffusion. This process is saturable and sodium dependent and involves ATPase (McCormick, 1990). In riboflavin deficiency, there is enhanced uptake of riboflavin by intestinal brush border membrane vesicles associated with an increase in V_{max} rather than K_m for riboflavin (Said and Mohammadkhani, 1993). Similarly, there is down-regulation of V_{max} and no change in K_m when riboflavin status is restored. Prolongation of stomach emptying also enhances the bioavailability of pharmacological doses of riboflavin (Forusz and Ritschel, 1996). In a number of species, riboflavin-binding proteins have been identified in the plasma, and in their absence there is massive riboflavinuria. In human blood, the transport of flavins involves loose binding to albumin and tight binding to globulins especially the immunoglobulins (IgA, IgG, and IgM). Serum binding proteins also appear to be involved in the placental transport of riboflavin. The main route of riboflavin excretion from the body is via urine as riboflavin. Neither FMN nor FAD is present in urine. In humans, about 60 to 70 percent of the riboflavin excreted is in the free form, the balance being present as various metabolites (McCormick, 1994). In dogs, urinary excretion of riboflavin and extrarenal metabolism and/or excretion contribute almost equally to the overall elimination rate. Since renal clearance exceeds the glomerular filtration rate in dogs and in humans, part of the clearance of riboflavin occurs by tubular secretion (Jusko et al., 1970).

Biological Function

The major function of riboflavin is to serve as a precursor of the coenzymes FMN and FAD. Synthesis of the coenzymes from riboflavin is under the control of thyroid hormones. The initial step involves the phosphorylation of riboflavin to FMN catalyzed by the enzyme flavokinase; this is followed by conversion of FMN to FAD. These coenzymes catalyze a number of oxidation-reduction reactions. FAD is part of the respiratory chain and therefore is central to energy metabolism. In addition many kinds of oxidation-reduction reactions are catalyzed by flavoproteins, such as dehydrogenation, hydroxylation, oxidative decarboxylation, dioxygenations, and reduction of oxygen to hydrogen peroxide (Rivlin and Pinto, 2001). The redox functions of riboflavin are both one-electron and two-electron transfers from substrate to the flavin coenzyme.

While riboflavin does not have significant inherent antioxidant capacity, it plays a key role in the glutathione redox cycle. The selenium-containing enzyme glutathione peroxidase catalyzes the reduction of lipid peroxides to hydroxy acids before they are metabolized, and in the process reduced glutathione is oxidized. Regeneration of reduced glutathione is dependent on the FAD-containing enzyme glutathione reductase.

The measurement of erythrocyte glutathione reductase activity (EGRA) is the preferred index of riboflavin status, but few measurements have been reported in dogs and none in cats.

Dogs

Signs of Deficiency

Acute riboflavin deficiency results in anorexia, body weight loss, decreased activity, hypothermia, decreased respiratory rate, progressive weakness, ataxia, sudden collapse to a semicomatose state, and death (Street and Cowgill, 1939). Chronic riboflavin deficiency has been associated with anorexia, body weight loss, muscular weakness, flaking dermatitis of the abdomen and medial surface of the hind legs, and ocular lesions. The ocular lesions were generally bilateral and were evident as opacity of the cornea often associated with vascularization and watery or purulent discharge from the eye (Street et al., 1941; Potter et al., 1942; Heywood and Partington, 1971; Noel et al., 1972).

Requirements

Street and Cowgill (1939) gave three groups of adult dogs a purified diet based on casein, sucrose, vegetable fat,

and minerals, plus an extract from rice polishings to supply B vitamins other than riboflavin, and cod liver oil. Group 1 dogs received the diet alone; group 2 consisted of one dog given the same diet plus 4 to 8 μg riboflavin·kg BW^{-1} ·d^{-1}. Three of the dogs in group 3 were pair-fed the basal diet of dogs in group 1 and given 25 μg riboflavin·kg BW^{-1} ·d^{-1}. Group 1 dogs had a reduction of food intake 2 to 11 weeks after initially receiving the diet, and five of the six dogs entered a collapsed state after 120 ± 8 days when they exhibited a reluctance to walk or a staggering gait and passed into a comatose state. The dog receiving 4 to 8 μg riboflavin·kg BW^{-1}·d^{-1} collapsed after 332 days. All dogs receiving 25 μg of riboflavin maintained good health although they had restricted food intakes. The authors concluded that 25 μg of riboflavin·kg BW^{-1}·d^{-1} was adequate for maintenance of adult dogs. Street et al. (1941) using the same purified diet confirmed this finding and described neurological abnormalities in dogs given low intakes of riboflavin.

Axelrod et al. (1940, 1941) gave weaned pups a purified diet plus 1, 2, or 4 mg riboflavin·kg^{-1} diet. These authors concluded that for growing puppies, 2 mg riboflavin·kg^{-1} diet was inadequate, but 4 mg riboflavin·kg^{-1} diet was adequate. Potter et al. (1942) gave puppies a purified diet that supplied 8.6 μg of riboflavin·kg^{-1} and a riboflavin supplement on alternate days equivalent to 60 or 100 μg riboflavin·kg BW^{-1}·d^{-1}. They concluded that the riboflavin requirement for growing puppies lies between these values. Unlike thiamin, isocaloric substitution of sucrose in the diet with lard had no effect on riboflavin requirement.

Spector et al. (1943) gave young and adult dogs variable levels of riboflavin and subjected them to repeated phlebotomy. They suggested that 15 and 30 μg riboflavin·kg BW^{-1}·d^{-1} were necessary for adult and young dogs respectively for hemoglobin production and rapid recovery from anemia. However, Heywood and Partington (1971) reported that the proposed requirement of 30 μg· kg BW^{-1}·d^{-1} was inadequate to prevent one in four growing dogs given a purified diet from developing corneal opacities. Noel et al. (1971) gave three groups of six (three male and three female) 12- to 14-week-old beagles a purified diet with 120, 90, or 50 μg riboflavin·kg BW^{-1}·d^{-1} for 9 weeks. After 9 weeks the riboflavin intake of the female dogs was reduced to 30 μg·kg BW^{-1}·d^{-1} for the following 8 weeks. Dogs given 30 μg of riboflavin·kg BW^{-1}·d^{-1} from week 10-12 to week 17 lost body weight. The authors concluded that 30 μg·kg BW^{-1}·d^{-1} was too low to keep growing beagles in good health and that 88 μg·kg BW^{-1}·d^{-1} was marginally high.

Cline et al. (1996) conducted a study on the riboflavin requirement of adult dogs using the erythrocyte glutathione reductase activity coefficient (EGRAC) as a determinant of riboflavin requirement. These authors used diets that contained 1.7, 2.7, 3.7 4.7, and 5.7 mg riboflavin·kg^{-1}. There was no difference in EGRAC in dogs given diets containing 2.7 to 5.7 mg·kg^{-1}, but dogs given 1.7 mg·kg^{-1} had significantly higher EGRAC. These authors estimated that the adult dog at maintenance had a riboflavin requirement of 67 μg·kg BW^{-1}·d^{-1}. It is suggested that a daily intake of 70 μg·kg BW^{-1}·d^{-1} be used for adult dogs, which is equivalent to 1.05 mg per 1,000 kcal for maintenance. In the absence of EGRAC information on growing puppies or pregnant and lactating bitches, the same dietary concentration is recommended; 1.05 mg riboflavin per 1,000 kcal. These values are greater than those proposed by the NRC (1985) for growing puppies. ABGE (1989) recommended daily allowances of 50 and 100 μg·kg BW^{-1} for maintenance and growth, respectively.

Hypervitaminosis

Unna and Greslin (1942) gave four 10-week-old dogs 25 mg riboflavin·kg BW^{-1} for 5 months and reported normal growth and an absence of adverse clinical signs. Macroscopic examination of the organs failed to indicate any abnormalities. These authors also reported that dogs would tolerate a single dose of 2 g riboflavin·kg BW^{-1}. Riboflavin is more toxic when administered parenterally than orally. The NRC (1987) gave estimated rat LD_{50} values for intraperitoneal, subcutaneous, and oral routes of 0.56, 5, and greater than 10 g·kg BW^{-1}, respectively. The safe upper concentration of riboflavin in the diet of dogs has not been defined.

Cats

Signs of Deficiency

Gershoff et al. (1959a) reported that in acute riboflavin deficiency, cats exhibited anorexia, loss of body weight, and periauricular alopecia with epidermal atrophy. In chronic riboflavin deficiency, cats developed cataracts, fatty livers, and testicular atrophy.

Requirements

Gershoff et al. (1959) studied the effect of carbohydrate level in the diet on riboflavin requirements of cats. These authors gave 3- to 6-month-old kittens either a high-fat diet (46 percent of ME from fat) or a low-fat (11 percent of ME from fat) diet. The authors concluded that a high-carbohydrate, low-fat diet favored microbial synthesis of riboflavin as indicated by a greater fecal and urinary excretion of riboflavin than for cats given a low-carbohydrate, high-fat diet. It is likely that the diet would have promoted extensive microbial fermentation and possibly synthesis of riboflavin in the gut since it contained 50 percent sucrose. These authors reported that two cats maintained excellent health for more than 34 months on the high-carbohydrate diet plus 3 mg riboflavin·kg^{-1} diet and that cats were routinely reared in their laboratory on a low-carbohydrate, high-fat diet containing 4 mg riboflavin·kg^{-1} for 2 years.

Leahy et al. (1967) used a depletion-repletion study to determine riboflavin requirements of kittens. These authors gave five groups of kittens (initial body weight about 700 g) a riboflavin-free purified diet for 28 days, and then supplemented with 0, 25, 50, 100, or 200 μg riboflavin per kitten per day for another 28 days. A sixth group was given 200 μg per day riboflavin for the entire period. A necropsy was performed on all kittens at the end of the 56 days but did not reveal any gross pathological changes. Weight gain during the first 28 days was depressed, and some kittens lost body weight, which may have been due to poor acceptance of the purified diet. All groups including the unsupplemented kittens gained weight from day 29 to 56, but weight gain was maximal in the group given 100 μg riboflavin per kitten per day. Although the authors stated that the requirement did not exceed 100 $\mu g \cdot d^{-1}$ or 1 $mg \cdot kg^{-1}$ diet, based on weight gain, this requirement is probably too low. A requirement of 4 $mg \cdot kg^{-1}$ diet (5.0 $kcal \cdot g^{-1}$) was suggested by the NRC (1986) or 800 μg per 1,000 kcal of diet. In view of the limited information available, it is suggested that this requirement be maintained as an adequate intake for growth, maintenance, and lactation. This dietary concentration is equivalent to an intake of 79 $\mu g \cdot kg\ BW^{-0.67} \cdot d^{-1}$ for a 4-kg adult cat consuming 250 kcal of ME per day.

Hypervitaminosis

There are no reports of riboflavin toxicity in cats. Although riboflavin is a water-soluble vitamin, it is not well absorbed when given in doses exceeding requirements. Presumed safe upper concentrations were not proposed for riboflavin by the NRC (1987). The SUL of riboflavin in the diets of cats has not been defined.

VITAMIN B_6

Vitamin B_6 is a generic descriptor for all 3-hydroxy-2-methylpyridine derivatives, including pyridoxine, pyridoxal, pyridoxamine, and their phosphorylated forms. The coenzyme form of the vitamin is pyridoxal-5′-phosphate, which is covalently bound by a Schiff's base to an ε-amino group of lysine of the enzyme.

Absorption, Transport, and Storage

Most vitamin B_6 in foods is present as phosphorylated derivatives of pyridoxine, pyridoxal, and pyridoxamine. The predominant forms in animal tissue foods are pyridoxal and pyridoxamine, whereas in plant foods the major forms are pyridoxine and pyridoxamine. In addition to phosphorylated derivatives, plant foods also contain glycosylated forms of vitamin B_6, which may have a negative effect on bioavailability (Leklem, 2001)

Phosphorylated forms of the vitamin are absorbed from the intestine of rats to only a limited extent and are hydrolyzed by alkaline phosphatase before absorption. Absorption of pyridoxine, pyridoxal, and pyridoxamine occurs by a nonsaturable passive process (Henderson, 1985). These three nonphosphorylated forms are converted to their respective phosphorylated forms by pyridoxine kinase. The two phosphorylated forms pyridoxine-5′-phosphate and pyridoxamime-5′-phosphate are converted to pyridoxal-5′-phosphate by an FMN-requiring oxidase.

The liver is the primary organ for metabolism of vitamin B_6, and releases the active form of the vitamin (pyridoxal-5′-phosphate, PLP) into the circulation to supply other tissues. Low riboflavin status lead to a reduction in circulating PLP. PLP formed in the liver and other tissues can combine with proteins via a Schiff's base reaction. The binding of PLP to proteins may be the major factor in determining tissue concentrations of the vitamin. In plasma, PLP produced and released by the liver is bound to albumin, which may protect it from hydrolysis until it is delivered to various tissues. Uptake of vitamin B_6 by cells is thought to occur by hydrolysis of the phosphate group of PLP by phosphatases at the cell's surface.

In muscle, most vitamin B_6 is present as PLP bound to glycogen phosphorylase. Because of this association and the large mass of muscle in the body, it has been suggested that muscle is the main storage site for vitamin B_6. However, in rats and swine, muscle PLP is mobilized during an energy deficit, but not during a dietary deficiency of B_6. Under conditions of strenuous exercise and energy deficit, muscles may release B_6 and result in increased circulating levels of PLP.

In many species, an end product of vitamin B_6 metabolism is pyridoxic acid, which is excreted in urine. Coburn and Mahuren (1987) reported that cat urine contained little pyridoxic acid after dosing with large amounts of pyridoxine hydrochloride. The main metabolites were 50 percent pyridoxine 3-sulfate and 25 percent *N*-methylpyridoxine. At low pyridoxine intakes, the excretion of pyridoxal 3-sulfate exceeded that of pyridoxine 3-sulfate.

Biological Function

More than 100 enzymatic reactions have been reported in which PLP is a coenzyme, and nearly half involve transamination-type reactions (Sauberlich, 1985). Beside transamination reactions involving the α-carbon, other reactions involving pyridoxal phosphate include racemization, decarboxylation, oxidative deamination, and side-chain elimination. Additional reactions include those involving the β-carbon (replacement and elimination reactions) and the γ-carbon (replacement, elimination, and cleavage reactions).

Because of the multiplicity of enzymatic reactions involving PLP, it follows that PLP plays a role in a wide range of physiological processes including gluconeogenesis, erythrocyte function, niacin synthesis, nervous system function, immune response, lipid metabolism, hormone modulation, and gene expression (Leklem, 2001). In gluco-

neogenesis, PLP is a coenzyme in transamination reactions and also for glycogen phosphorylase. An inadequacy of PLP in rats results in lowered activities of alanine and aspartate aminotransferases and liver and muscle phosphorylase. In the synthesis of hemoglobin, PLP serves as a cofactor for δ-aminolevulinic acid synthetase, which catalyses the condensation of glycine and succinylcoenzyme A to δ-aminolevulinic acid; this latter compound is a precursor of heme, and vitamin B_6 deficient-animals develop hypochromic microcytic anemia. In addition, pyridoxal and PLP bind to hemoglobin, thereby changing its affinity for oxygen.

PLP functions in at least four enzymatic reactions in the complex tryptophan-niacin pathway. Only one reaction is in the direct pathway of conversion; the other three are side pathways that do not lead to niacin. However, it is the direct involvement of PLP in tryptophan metabolism that is the basis of the tryptophan loading test for vitamin B_6 deficiency.

In nervous tissue, PLP is also involved in another tryptophan pathway—the conversion of 5-hydroxytryptophan to 5-hydroxytryptamine, which is catalyzed by the PLP-dependent enzyme 5-hydroxytryptophan decarboxylase. Synthesis of other neurotransmitters such as taurine, dopamine, norepinephrine, histamine, and γ-aminobutyric acid also requires PLP. One of the main clinical signs observed in vitamin B_6 deficiency in cats is the involvement of PLP in neurotransmitter production.

PLP serves as a coenzyme for serine transhydroxymethylase, which catalyzes the transfer of a one-carbon moiety to tetrahydrofolate, allowing thymidylate and nucleic acid synthesis. In some animal studies, vitamin B_6 deficiency has been shown to adversely affect lymphocyte production and antibody response.

There is evidence from studies in rats that vitamin B_6 deprivation may impair the conversion of linoleic acid to arachidonic acid. It has been suggested that linoleic desaturation and γ-linolenic elongation may be adversely affected by vitamin B_6 deficiency. This is of particular interest in cats, which have a low efficiency of conversion of linoleic to arachidonic acid.

PLP has been shown to be a modulator of steroid action (Brandsch, 1994; Tully et al., 1994), and to undergo reversible reactions with the receptors for estrogens, androgens, progesterone, and glucocorticoids. PLP reacts with a lysine residue on the steroid receptor to form a Schiff's base.

Pyridoxal phosphate is the main form of vitamin B_6 in the plasma of replete cats, the ratio of PLP to PL being about 5:1 (Bai et al., 1989), whereas in vitamin B_6-replete rats the ratio is about 1:1 (Sampson and O'Connor, 1989).

Dogs

Signs of Deficiency

Acute vitamin B_6 deficiency in newly weaned puppies produced anorexia, body weight loss, and death before any marked hematological changes occurred. In older dogs and adults, clinical signs also include convulsions, muscle twitching, and microcytic hypochromic anemia (Fouts et al., 1938, 1939; McKibbin et al., 1939, 1942). Street et al. (1941) described a range of pathological changes in addition to the above that included ataxia, cardiac dilation and hypertrophy, congestion of various tissues, and demyelination of peripheral nerves.

Requirements

Fouts et al. (1938) showed that a purified diet including an extract of rice polishings (a source of vitamin B_6) produced normal growth and hematology in weaned puppies, but when the extract was not included in the diet, convulsions and severe microcytic hypochromic anemia occurred. The rice bran extract was later found to supply the equivalent of 60 μg of pyridoxine·kg BW^{-1}·d^{-1} to adult dogs (Fouts et al., 1939), a quantity shown by McKibbin et al. (1939) to correct anemia. Street et al. (1941) produced vitamin B_6 deficiency in adult dogs given a semipurified diet and reported that in one dog an estimated 5 μg of pyridoxine·kg BW^{-1}·d^{-1} from a concentrate was inadequate, but 10 μg·kg BW^{-1}·d^{-1} was adequate. In unpublished experiments quoted by Michaud and Elvehjem (1944), growing dogs given 5 μg of pyridoxine·kg BW^{-1}·d^{-1} died before the appearance of anemia; 10 μg·kg BW^{-1}·d^{-1} gave fairly good growth but was not as good as 60 μg·kg BW^{-1}·d^{-1}. The authors suggested that 10 μg·kg BW^{-1}·d^{-1} may be adequate for maintenance. There do not appear to be any critical studies on the vitamin B_6 requirement of dogs since reviewed by the NRC (1985). Therefore, an adequate intake of 1.1 mg·kg^{-1} diet (3.67 kcal·g^{-1}) or 0.3 mg per 1,000 kcal for growing puppies is retained. This dietary concentration is equivalent to 84 μg·kg $BW^{0.75}$·d^{-1} for puppies for growth, and 39 μg·kg $BW^{0.75}$·d^{-1} for adult dogs for maintenance. In the absence of futher information, it is assumed that a dietary concentration that satisfied the requirements for growth would meet the needs for pregnancy and lactation. These recommendations are similar to those of ABGE (1989). For a diet with an ME of 4 kcal·g^{-1}, these daily amounts are supplied with approximately 1.2 mg pyridoxine·kg^{-1} diet.

Hypervitaminosis

Unna and Antopol (1940) reported that puppies given 20 mg of pyridoxine·kg BW^{-1} for 75 or 80 days did not develop signs of toxicity, had normal hematology, and showed no pathological changes. An acute dose of 1 g pyridoxine·kg^{-1} produced impairment of coordination and tonic convulsions. Chronic dosing with 200 mg pyridoxine hydrochloride·kg BW^{-1}·d^{-1} produced ataxia, muscle weakness, and loss of balance between 40 and 75 days (Phillips et al., 1978). Higher doses of 250 mg·kg BW^{-1}·d^{-1} resulted in impaired coordination and ataxia within a week of treatment. Bilateral loss of myelin and axons in the dorsal funiculi and loss of myelin in

individual fibers of the dorsal root were found on necropsy. A lesser degree of pathological damage was found in dogs receiving 50 mg pyridoxine hydrochloride·kg $BW^{-1}·d^{-1}$. Krinke et al. (1980) administered daily oral doses of 300 mg pyridoxine hydrochloride·kg BW^{-1} to 7- to 11-month-old beagle dogs for 78 days. Locomotor abnormalities developed within 9 days, and eventually the dogs were unable to walk even though they did not exhibit muscular weakness. The authors concluded that pyridoxine produced a toxic peripheral sensory neuropathy that involved neuronal degeneration of dorsal root ganglia and sensory nerve fibers. Hoover and Carlton (1981) administered daily doses of pyridoxine hydrochloride to beagles beginning with 15 mg·kg BW^{-1}. The dose was increased to 150 mg·kg BW^{-1} by the 15th day and continued at that level for 85 days. Anorexia developed within 2 weeks and ataxia within 4 weeks.

The NRC (1987) proposed presumed safe upper dietary levels for dogs of 1,000 mg pyridoxine·kg^{-1} diet for less than 60 days and 500 mg·kg^{-1} diet for periods longer than 60 days. A safe upper concentration of pyridoxine in the diet of dogs has not been defined.

Cats

Signs of Deficiency

Vitamin B_6 deficiency in cats has been more recently investigated than in dogs. Carvalho da Silva et al. (1959) reported growth depression, mild microcytic hypochromic anemia, convulsive seizures, and kidney lesions in cats given vitamin B_6-deficient diets. These lesions of the kidney were shown by Gershoff et al. (1959) to be due to the presence of calcium oxalate monohydrate crystals, and the urine of vitamin B_6-deficient cats contained calcium oxalate. A description of the renal lesions resulting from vitamin B_6 deficiency has been given by Blanchard et al. (1991). Bai et al. (1989) reported clinical signs similar to those described by Carvalho da Silva et al. and Gershoff et al. as well as elevated plasma concentrations of tyrosine in pyridoxine-deficient cats. The total activity of the first enzyme of tyrosine degradation (tyrosine aminotransferase, TAT) was shown by Bai et al. (1998) to be depressed in pyridoxine-deficient cats. The apparent K_m of hepatic TAT from cats for tyrosine was similar to that of rats (2.1 vs. 1.9 mmol·L^{-1}, respectively), but the apparent K_m of TAT from cats for PLP was much higher than that from rats.

Requirements

Carvalho da Silva et al. (1959) reported that 1 mg of pyridoxine given orally three times a week would prevent clinical signs of deficiency and support a normal hemogram in 3- to 4-month-old kittens given a semipurified diet. Gershoff et al. (1959) using 3- to 6-month-old kittens also fed a purified diet reported that 1 mg of pyridoxine hydrochloride per kilogram of diet was inadequate, but 2 mg·kg^{-1} diet resulted in normal growth and hematology. Since urinary excretion of oxalate was greater in cats given diets of 2 mg pyridoxine hydrochloride per kilogram of diet than those given 4 mg·kg^{-1}, the higher level was recommended by the NRC (1986). Subsequent depletion-repletion studies by Bai et al. (1989) using additional criteria confirmed that a concentration of 1 mg pyridoxine·kg^{-1} diet was inadequate for growing kittens, but 2 mg·kg^{-1} diet was adequate when the diet contained 350 g·kg^{-1} casein. In a further depletion-repletion study, Bai et al. (1991) demonstrated that the vitamin B_6 requirement of cats depended on protein concentration in the diet. For a diet of 300 g casein·kg^{-1} the vitamin B_6 requirement could be met with 1 mg pyridoxine·kg^{-1} diet, whereas for a diet containing 600 g casein·kg^{-1} the requirement was greater than or equal to 2.0 mg pyridoxine·kg^{-1} diet. To accommodate high-protein diets up to about 500 g protein·kg^{-1}, a minimal pyridoxine requirement of 2 mg·kg^{-1} diet or 500 µg per 1,000 kcal is proposed for cats of all physiological states. This dietary concentration will provide 49 µg·kg $BW^{-0.67}·d^{-1}$ for an adult cat at maintenance.

Hypervitaminosis

There are no reports of studies on the toxicity of vitamin B_6 in cats. The presumed SUL of pyridoxine in the diet of rats is 250 mg·kg^{-1} for periods of more than 60 days (NRC, 1987). The safe upper concentration of pyridoxine in the diets of cats has not been defined.

NIACIN

Dogs played an important role as models for study of the human disease pellagra and in testing the antipellagra activities of preparations and foods (Harvey et al., 1938; Carpenter, 1991). Chittenden (1907) described clinical signs of disturbances of the gastrointestinal tract with bloody discharge and inflammation of the mucous membranes of the mouth in a dog given a diet of bread and lard. The similarities between these clinical signs in dogs, referred to as "black tongue," and those of pellagra in humans were recognized by Goldberger and colleagues (Goldberger and Wheeler, 1920, 1928; Wheeler et al., 1922). A major contribution of Goldberger was the recognition that a pellagra-preventive factor ("P-P factor") was missing in corn, and the disease was not due to an infectious or toxic agent. Elvehjem et al. (1937, 1938) showed that the P-P factor was nicotinic acid or nicotinic acid amide, which would cure black tongue in dogs. This observation was also confirmed by Street and Cowgill (1937). However, analysis of corn showed that it was not particularly low in nicotinic acid, a problem that was resolved by Laguna and Carpenter (1948) who demonstrated that the niacin in corn was released only after prolonged exposure to high pH and normally was poorly bioavailable. While niacin would cure

pellagra, it was also known that certain proteins such as casein would reverse pellagra in rats. This anomaly was resolved when it was demonstrated that tryptophan could be used with low efficiency for the synthesis of nicotinamide-adenine dinucleotide (NAD) (Heidelberger et al., 1948).

Whereas dogs are able to synthesize nicotinamide endogenously from tryptophan, cats do not produce any measurable quantities. Carvalho da Silva et al. (1952) reported that there was no increase in urinary excretion of *N*-methylnicotinamide after administration of a tryptophan load to cats. The extent of conversion of tryptophan to nicotinic acid is determined by the fate of α-amino-β-carboxymuconic-ε-semialdehyde, an intermediate in tryptophan metabolism that is involved in two competing metabolic pathways. One results in the production of acetyl-CoA and CO_2 and the other, NAD. Picolinic carboxylase is the enzyme catalyzing the first step of the degradative pathway to acetyl-CoA and CO_2, and across species the dietary niacin requirement is related directly to the hepatic activity of this enzyme (Ikeda et al., 1965; Scott, 1986). Cats possess all the enzymes of the pathway of niacin synthesis, but the activity of picolinic carboxylase is extremely high, the highest of all animals studied (Sudadolnik et al., 1957; Ikeda et al., 1965), precluding any measurable synthesis of nicotinic acid (Carvalho da Silva et al., 1952; Leklem et al., 1971). Meat is well supplied with the NAD and NADP (nicotinamide-adenine dinucleotide phosphate) coenzymes, and while cats consume a diet of animal tissue there is no need to produce niacin from tryptophan. The direct production of acetyl-CoA may be energetically more efficient for cats than the oxidation of NAD or the intermediates of the NAD pathway

Absorption

The majority of niacin in plant foods is present as nicotinic acid, but animal tissues initially contain NAD and NADP coenzymes, which, under post mortem anaerobic conditions, are in part converted to the reduced forms. Of the free niacin present in animal tissues, most occurs as nicotinamide. A high proportion of the niacin in plant foods is not available and may be in the bound form. Ghosh et al. (1963) using a microbiological assay reported that 85 to 90 percent of the total nicotinic acid in cereal grains was in the bound form. The nature of the binding of nicotinic acid in wheat bran was investigated by Mason et al. (1973). These authors reported binding of nicotinic acid to macromolecules with a molecular weight of 1,500 to 17,000 Da, of which about 60 percent were polysaccharides and 40 percent peptides. Carter and Carpenter (1982) developed a rat assay for available niacin in foods and reported that mature cooked cereals gave values of about 35 percent of the total niacin content. In calculating the niacin content of diets for dogs and cats, the niacin contribution from cereals should be either ignored or given an available value no greater than one-third of the total niacin.

Synthesis of niacin by microbes occurs in the intestine of rats (Tepley et al., 1947), and presumably some also occurs in the intestine of dogs; however the extent of synthesis does not appear to have been quantified.

The primary site of absorption of both nicotinamide and nicotinic acid is the proximal small intestine, although some absorption occurs in the stomach. In the small intestine, pyrophosphatase metabolizes NAD to nicotinamide mononucleotide, which is hydrolyzed to nicotinamide riboside and eventually to free nicotinamide (Kirkland and Rawlings, 2000). Absorption at low concentrations of both nicotinic acid and nicotinamide appears to occur by sodium-dependent facilitated diffusion (Henderson, 1983) or by carrier-mediated transport using proton cotransporters and anion antiporters (Takanga et al., 1996). At higher concentrations, both forms appear to be absorbed by passive diffusion. Once in the enterocyte, nicotinamide may be converted to NAD or released into the portal circulation.

Biological Function

Niacin is the general descriptor for vitamers having the biological activity associated with nicotinamide, including nicotinamide, nicotinic acid, and a variety of pyridine nucleotide structures (Kirkland and Rawlings, 2000). NAD and NADP are the two natural pyridine nucleotide coenzymes derived from niacin. These coenzymes function in numerous oxidoreductase systems usually of the dehydrogenase-reductase type. The carbon in the C-4 position on the pyridine ring of the nucleotide moiety participates in oxidation-reduction reactions and is the basis for hydrogen transfer reactions in oxidative phosphorylation and in biosynthetic reactions. The electronegativity of the amide group and the nitrogen in position 1 of the ring permit hydride ions to readily reduce the oxidized carbon in position 4. NAD(H) (reduced NAD) plays an essential role in energy expenditure reactions, whereas NADP(H) is essential in many synthetic reactions including those involving energy storage. NADP(H) is produced by reduction of $NADP^+$ (oxidized NADP) in reactions of the pentose phosphate pathway and during the malate shuttle across the mitochondrial membrane. NADP(H) provides the reducing equivalents for fatty acid synthesis and the regeneration of oxidized glutathione.

Nicotinamide coenzymes also participate in non-redox reactions that involve mono- and poly(ADP-ribosyl)ation (ADP = adenosine diphosphate) reactions, which are substrate rather than coenzyme functions. The high-energy glycosidic linkage between nicotinamide and ADP-ribose participates in these reactions, and the energy provided by breaking this bond allows for the transfer of ADP-ribose to nucleophilic acceptors. These include glutamate side chains and hydroxyl groups of ribose for poly(ADP-ribose) synthesis, a variety of amino acid side chains in mono(ADP-ribosyl)ation reactions, and an internal ribose linkage for cyclic ADP-ribose synthesis (Kirkland and Rawlings, 2000). A

number of studies have demonstrated poly(ADP-ribosyl)-ation of enzymes involved in DNA repair, transcription, and replication. In certain human populations, an association between an inadequate intake of niacin in the diet and the incidence of certain type of cancers has been made.

Urine is the main route of excretion of products arising from the metabolism of nicotinic acid. In dogs these products are trigenolline (3-carboxy-1-methypyridinium) (75-94 percent) and nicotinic acid (6 to 25 percent) (Sarett, 1942).

Dogs

Signs of Deficiency

The following clinical signs have been reported in niacin deficiency in dogs: anorexia and body weight loss; reddening of the inside of the upper lip that progresses to inflammation and ulceration of the buccal and pharyngeal mucosa; vermilion bands on the lips; profuse salivation with ropy, blood-stained saliva drooling from the mouth; and a fetid odor. Dogs also developed bloody diarrhea, and intestinal absorption of water, glucose, sodium, and potassium was reduced. Diarrhea may be a consequence of the shortening and clubbing of villi and inflammation and degeneration of the mucosa. Neuronal degeneration of the spinal cord and distortion of conditioned reflexes have also been observed, along with hepatic periportal fatty metamorphosis. No marked gross changes were observed in the gastric mucosa other than mild hyperemia and pallor. A reduction in urinary excretion of *N*-methylnicotinamide and in the concentrations of NAD and NADP in liver and, to a lesser degree, in muscle has been reported. Uncorrected deficiencies lead to dehydration, emaciation, and death (Dann and Handler, 1941; Sarett, 1942; Schaefer et al., 1942; Handler, 1943; Smith et al., 1943; Layne and Carey, 1944; Nelson et al., 1963; Belavady and Gopalan, 1965; Greengard et al., 1966; Madhavan et al., 1968; Manson and Carpenter, 1978).

Requirements

Sebrell et al. (1938) gave 6- to 8-kg dogs (presumably adult) a corn-based diet (modified Goldberger diet) and twice-weekly injections of nicotinic acid. On a daily body weight basis, 126 μg nicotinic acid·kg^{-1} resulted in incipient signs of disease, whereas 340 μg·kg^{-1} prevented black tongue. Margolis et al. (1938) produced black tongue in adult dogs by using a modified Goldberger diet. They reported that 500 μg or more nicotinic acid·kg BW^{-1}·d^{-1} cured the disease, whereas with 200 μg nicotinic acid·kg BW^{-1}·d^{-1} the response was delayed and 100 μg·kg BW^{-1}·d^{-1} was ineffective. Birch (1939) also used a corn-based diet and reported that while 130 μg nicotinic acid·kg BW^{-1}·d^{-1}prevented signs of black tongue and permitted some body weight gain in depleted adult dogs, 250 μg·kg BW^{-1}·d^{-1} allowed for rapid weight gain. Lower doses of 27 and 84 μg·kg BW^{-1}·d^{-1} gave no protection.

Schaefer et al. (1942) were the first to attempt to define the niacin requirements of dogs using a purified diet. The diet used was fortified with thiamin, riboflavin, pyridoxine, pantothenic acid, and choline. The requirements they determined for adult dogs were 200 to 225 μg·kg BW^{-1}·d^{-1} and for growing dogs 250 to 365 μg·kg BW^{-1}·d^{-1}. The contribution of the tryptophan in casein to the niacin equivalents of the diet was not calculated, but a diet that contained 660 g·kg^{-1} of acid-washed casein would have supplied about 7.9 g tryptophan·kg^{-1} diet. If dogs converted all of the tryptophan to niacin at the same efficiency (60:1) as reported for humans (Howitt et al., 1981), the basal diet would have contributed about 132 mg niacin equivalents per kilogram from tryptophan.

Singal et al. (1948) gave growing dogs a semipurified niacin-free diet based on 66 percent sucrose and 19 percent casein. They reported that when 21 percent of the sucrose in the basal diet was replaced with an equal weight of low-tryptophan proteins (zein or gelatin), there was no change in the time for the dogs to be depleted. However when 21 percent of the sucrose was replaced with casein, a protein high in tryptophan, about twice as much weight gain occurred before depletion. Although none of these diets prevented clinical signs of niacin deficiency, a diet in which 42 percent of the sucrose was replaced by casein afforded complete protection from niacin deficiency. Similarly, complete protection from niacin deficiency was obtained by adding 0.5 percent L-tryptophan to the basal diet.

The efficiency of utilization of the D- vs. L-isomer of tryptophan for growth by dogs was examined by Czarnecki and Baker (1982). They reported that D-tryptophan was used with an efficiency of only 35 percent of that of L-tryptophan and that 15 percent of D-tryptophan was recovered in the urine, whereas no measurable tryptophan was found in the urine of dogs given L-tryptophan.

At least two factors are responsible for the association of pellagra in humans and black tongue in dogs with the consumption of corn. First, a high proportion of the niacin in corn is bound and of low availability (Chaudhuri and Kodichek, 1960); second, the tryptophan concentration in corn is lower than in most other cereals. It has also been suggested (Belavady and Gopalan 1965; Belavady et al., 1967; Gopalan et al., 1969) that high levels of leucine in jowar (*Sorghum vulgare*) may be a secondary factor in the production of pellagra in humans and black tongue in dogs. However, workers in other laboratories (Truswell et al., 1963; Nakagawa and Sasaki, 1977; Manson and Carpenter, 1978) were not able to reproduce niacin deficiency by using purified diets high in leucine.

The studies of Schaefer et al. (1942) indicated niacin requirements of growing puppies and adult dogs of 365 and 225 μg·kg BW^{-1}·d^{-1} respectively. The NRC (1986) suggested that, for diets containing minimal quantities of tryp-

tophan, the daily requirement of adult dogs is met by 225 µg of niacin·kg BW^{-1} and of growing dogs by 450 µg niacin·kg BW^{-1}. In the absence of more recent information, it is proposed that 3.4 mg niacin per 1,000 kcal ME be used for all dogs. No published values could be found regarding the requirements for pregnancy and lactation, but the increased food intake associated with this physiological state should ensure adequate intake if the diet contains the requirement for growth. ABGE (1989) suggested allowances of 200 µg/kg $BW^{-1}·d^{-1}$ for maintenance and 450 µg·kg $BW^{-1}·d^{-1}$ for growth and reproduction.

Hypervitaminosis

Chen et al. (1938) reported that repeated oral doses of 2 g of nicotinic acid per day (133 to 145 mg·kg $BW^{-1}·d^{-1}$) produced bloody feces in two dogs by the 11th day of dosing, followed by convulsions and death. The NRC (1987) proposed that dietary intakes in excess of 350 mg nicotinic acid·kg $BW^{-1}·d^{-1}$ are toxic to animals in general. In view of the report by Chen et al. (1938), it is suggested that diets for puppies contain less than 0.5 g nicotinic acid·kg^{-1} (4 kcal·g^{-1}). Adult dogs may tolerate concentrations up to 1.0 g·kg^{-1} diet. The safe upper concentration of niacin in the diet of dogs has not been defined.

Cats

Signs of Deficiency

Heath et al. (1940) observed anorexia, elevated body temperature, a fiery red tongue with ulceration, and congestion in a clinical case that responded to nicotinic acid therapy. Carvalho da Silva et al. (1952) reported that young cats given purified diets without niacin ceased growing after 10 to 15 days, lost body weight, and died in 15 to 50 days. They exhibited unkempt hair and diarrhea, but no skin or buccal lesions or hematological changes. None of the 21 cats given a niacin-deficient diet was able to maintain weight gain after 20 days. Adult cats lost weight and eventually died. An association with respiratory disease was common and contributed to early deaths.

Requirements

Because cats are unable to convert the tryptophan to nicotinic acid, their total requirement of niacin must be derived from the diet. Heath et al. (1940) described feline pellagra in a clinical case of a 14-month-old cat whose lesions of the buccal cavity and inappetence resolved in 3 days after daily doses of 80 mg nicotinic acid. Carvalho da Silva (1950) reported that growing cats given a purified diet containing all vitamins (except niacin and cobalamin), with 2.5 mg nicotinic acid three times a week, had satisfactory growth, normal hemogram, and good health over a 12-month period. In a later report, Carvalho da Silva et al. (1952) stated that cats given a purified diet and supplemented with 4 mg of nicotinic acid three times a week maintained good health and referenced his earlier report (Carvalho da Silva, 1950). These authors concluded that "doses of 1 to 3 mg of niacin are effective against the deficiency; the optimum appears to be 10 mg or more." Braham et al. (1962) in relatively short-term experiments used *N*-methylnicotinamide excretion in urine as an index of niacin availability from corn-containing diets. They found adequate weight gains with a diet supplying 5 mg nicotinic acid per day. They also reported no difference in the *N*-methylnicotinamide of cats given raw and lime-treated corn, which could mean that the niacin was utilized to a similar extent or was not utilized since there were no controls.

The NRC (1986) proposed a minimal requirement of 40 mg nicotinic acid·kg^{-1} diet (5.0 kcal·g^{-1}) or 8.0 mg per 1,000 kcal ME. In the absence of other information, it is suggested that this requirement be maintained. This dietary concentration is equivalent to a daily intake of 0.8 mg·kg $BW^{-0.67}$. In formulating diets, the niacin contributed by cereals should be given a presumed bioavailability of 30 percent or disregarded.

Hypervitaminosis

There are no reports of adverse effects from excessive concentrations of nicotinic acid or nicotinamide in cats. A presumed safe level for all animals of 350 mg·kg $BW^{-1}·d^{-1}$ was suggested by the NRC (1987). The SUL of niacin in the diets for cats has not been defined.

PANTOTHENIC ACID

Pantothenic acid is an integral component of CoA, which is synthesized in animals by a series of steps that involve the initial phosphorylation of pantothenic acid to pantothenic acid 4′-phosphate catalyzed by pantothenate kinase, the primary regulatory step of CoA synthesis. This is followed by condensation with cysteine in an ATP-dependent reaction to form 4′-phosphopantothenoylcysteine, decarboxylation to yield 4′-phosphopantetheine, anhydride addition of adenosine 5′-monophosphate, and phosphorylation of the ribose 3′-hydroxyl group to produce CoA (Plesofsky, 2001). All of the enzymes for CoA synthesis occur in the cytosol, but mitochondria have the highest concentration of CoA.

Absorption, Transport, and Storage

Pantothenic acid is required by all forms of life; it is widely distributed in foods and deficiencies are rare. Most of the pantothenic acid in foods is contained in CoA, acyl-CoA synthetase, and an acyl carrier protein. Foods that are particularly high in panthothenic acid are organ meats (liver,

kidney), yeast, and egg yolk. Coenzyme A ingested in foods is hydrolyzed in the intestine to panthothenic acid, which is carried by a sodium-dependent transport system and absorbed by the enterocyte. Serum contains predominantly free pantothenic acid. Most cells take up pantothenic acid by cotransport with sodium ions. CoA is ultimately hydrolyzed in a series of steps to yield cysteamine and pantothenate which is excreted in the urine.

Dogs absorb free pantothenate efficiently from the gut. Taylor et al. (1974) reported that 81 to 94 percent of an oral dose of 6.68 mg of sodium [^{14}C]pantothenate was absorbed. Urinary excretion, principally as the β-glucuronide, represented the major route of excretion in dogs (Taylor et al., 1972). In distinction to other animals, little loss of the free vitamin occurs from the kidney of dogs, but excretion of the β-glucuronide approaches the glomerular filtration rate. Pantothenic acid in dehulled soybean meal has a bioavailability to chicks of 100 percent relative to crystalline pantothenic acid (Southern and Baker, 1981). The bioavailability of pantothenic acid in grains is lower, about 60 percent.

Only the dextrorotatory form of the vitamin (d-pantothenate) has vitamin activity. It may be prepared either as the pure dextrorotatory form or the dl-mixture, which has only half the biological potency of the dextrorotatory form. Pantothenic acid is an unstable, viscous oil that is extremely hydroscopic and destroyed by acids, bases, and heat. Calcium and sodium salts of pantothenic acid are the common forms of the vitamin used in dietary supplements (1 mg of pantothenic acid is equivalent to 1.087 mg of calcium pantothenate). Pantothenol, the alcohol derivative of pantothenic acid, is more stable than pantothenate and is used in some multivitamin preparations.

Biological Function

Coenzyme A and other pantothenate-containing molecules participate in two types of chemical reactions: acyl group transfer and condensation reactions. The free sulfhydryl group of CoA (derived from cysteine) is the active site of esterification of acetate or acyl groups. In acyl group transfer, there is nucleophilic addition to the carbonyl group thioesterified to CoA, followed by new ester bond formation and displacement of the CoA. Condensation reactions involve the acidification of the α-carbon of the acyl group thioesterified to CoA, and attachment of the α-carbon to an electrophilic center, leading to carbon-carbon bond formation or cleavage (Plesofsky, 2001).

Coenzyme A plays a central role in energy metabolism in oxidation of the products from glycolysis, β-oxidation of fatty acids, and other reactions in the tricarboxylic acid cycle. Acetyl-CoA condenses with oxaloacetate to yield citrate, which begins the oxidation of two-carbon residues in the cycle. Succinate feeds into the cycle as succinyl-CoA, which can contribute to gluconeogenesis. The synthesis of fatty acids and many essential compounds, such as steroids, cholesterol, and vitamin D, depend on CoA. Coenzyme A is also required through succinyl-CoA for the synthesis of the porphyrin rings of hemoglobin, and for acetylation reactions such as the synthesis of acetylcholine and acetylated sugars. Reactions that involve donation of an acetate group from CoA include the N-terminal (amino terminal) acetylation of proteins. The exposed N-terminus of 50 to 90 percent of soluble proteins is modified by acetate donated by CoA. Histones and α-tubulin undergo selective reversible acetylation of the ε-amino group of lysine residues. Coenzyme A is also involved in the acylation of a large number of proteins, principally by the addition of palmitate, myristate, or both.

Dogs

Signs of Deficiency

A pantothenic acid-deficient diet resulted in erratic food intakes of puppies within 2 to 3 weeks and adult dogs within 7 to 8 weeks (Sibler, 1944). Sudden prostration or coma, rapid respiratory and heart rates, convulsions, and gastrointestinal signs including gastritis, enteritis, and intussusception occurred in acutely deficient dogs (Schaefer et al., 1942). Reduced urinary excretion of the vitamin; reduction in the concentrations of pantothenate in blood, liver, muscle, and brain (Sibler, 1944) and reduced antibody production (Sheffy, 1964) have also been reported. On necropsy, Schaefer et al. (1942) reported that the livers were light colored and very high in fat (35-55 percent on a dry basis).

Requirements

Pantothenic acid was shown to be an essential dietary nutrient for dogs by McKibbin et al. (1939, 1940), Fouts et al. (1940), and Morgan and Simms (1940). Schaefer et al. (1942) further demonstrated the essentiality of pantothenic acid in the diet of dogs. These authors gave weanling puppies and adult dogs a diet of 660 g sucrose, 190 g acid-washed casein, 80 g cottonseed oil, 30 g cod liver oil, 40 g of a salt mixture per kilogram, and supplemented it with thiamin, riboflavin, nicotinic acid, pyridoxine, and choline. Growth ceased in the puppies after 3 to 4 weeks, and dogs died if not given pantothenic acid. Other litters were given graded doses of 0, 20, 40, 60, 100, and 150 μg of calcium pantothenate·kg $BW^{-1}·d^{-1}$. A daily calcium pantothenate supplement of 60 μg·kg BW^{-1} was inadequate, whereas either 100 or 150 $\mu g·kg^{-1}·d^{-1}$prevented the development of clinical signs of deficiency.

Sheffy (1964) depleted beagle puppies of pantothenate by feeding a complete purified diet lacking pantothenate for 4 to 5 weeks. Calcium pantothenate supplements were then given at approximately 0, 50, 100, 200, 500, and 1,000 $\mu g·kg\ BW^{-1}·d^{-1}$, and the dogs were given a single inoculation of a combination attenuated vaccine of distemper virus and infectious canine hepatitis virus. Puppies receiving the

0 and 50 μg pantothenate·kg BW^{-1}·d^{-1}died. There was no significant difference in the rate of body weight gain of puppies given 200, 500, and 1,000 μg·kg BW^{-1}·d^{-1}. Puppies given the highest two levels of supplementation had higher antibody titers at 7 days but not at 21 days than puppies receiving 200 μg·kg BW^{-1}·d^{-1}. Sheffy concluded that the requirement for growth was between 100 and 200 μg pantothenic acid·kg BW^{-1}·d^{-1}. Since a depletion-repletion protocol was followed, the higher levels of supplementation would give a more rapid repletion and an overestimation of the requirement.

The upper intake of 200 μg·kg BW^{-1}·d^{-1} for pantothenic acid suggested by Sheffy (1964) corresponds to an approximate dietary concentration of 1 mg per 1,000 kcal ME. The NRC (1985) proposed a value of 2.7 mg per 1,000 kcal ME for growing dogs. In the absence of more recent information, it is suggested that a dietary concentration of 3.0 mg per 1,000 kcal ME be used for all physiological stages of life. This dietary concentration is equivalent to an intake of 0.39 mg·kg $BW^{-0.75}$·d^{-1} for an adult dog at maintenance.

Hypervitaminosis

Pantothenic acid is generally regarded as nontoxic (Omaye, 1984). No cases of pantothenic acid toxicity in dogs have been reported. The NRC (1987) concluded that levels of 20 g pantothenic acid·kg^{-1} diet can be tolerated by most species.

Cats

Signs of Deficiency

Gershoff and Gottlieb (1964) reported failure to grow and histological changes as the main signs of pantothenate deficiency. The livers of kittens receiving 0, 1, or 3 mg calcium pantothenate·kg^{-1} diet had moderate to marked fatty metamorphosis and both fine and coarse vacuolar formation. Lesions of the gastrointestinal tract were confined to the small bowel and consisted of giant blunted villi in the jejunum and upper ileum.

Requirements

Gershoff and Gottlieb (1964) gave 3-month-old kittens a purified pantothenate diet, which was supplemented with 0, 1, 3, 5, 10, and 20 mg of calcium pantothenate·kg^{-1} diet. Kittens receiving 1 mg of calcium pantothenate died after 3.5 to 4 months; three of four kittens receiving the 3-mg diet died after 6 months; and one lived to 9 months. No deaths occurred in the cats given the diets of 5, 10, and 20 mg calcium pantothenate, and they had similar growth rates. All cats received an injection of *p*-aminobenzoic acid after receiving the diets for 3 months, and urinary excretion of acetylated and total *p*-aminobenzoic acid was measured. Kittens receiving the diets containing 5, 10, or 20 mg of calcium pantothenate had similar excretion of acetylated *p*-aminobenzoic acid. The authors concluded that 5 mg calcium pantothenate·kg^{-1} diet (or about 1.25 mg calcium pantothenate per 1,000 kcal ME) was a MR for growing kittens. In terms of pantothenic acid, this concentration is equivalent to 4.6 mg panthothenic acid·kg^{-1} diet or about 1.15 mg per 1,000 kcal ME. A dietary concentration of 1.25 mg per 1,000 kcal ME is equivalent to a pantothenic acid intake of 0.12 mg·kg $BW^{-0.67}$·d^{-1} for an adult cat at maintenance.

Hypervitaminosis

No cases of pantothenic acid toxicity in cats have been reported. The NRC (1987) concluded that levels of 20 g of pantothenic acid·kg^{-1} diet can be tolerated by most species (calcium pantothenate = 0.9201 pantothenic acid).

COBALAMIN (VITAMIN B_{12})

Cobalamin, the preferred name for the family of derivatives familiarly known as vitamin B_{12} (Beck, 2000), is unique among the vitamins in that it is synthesized only by certain microorganisms. Whenever cobalamins occur in nature, they are the result of synthesis by bacteria or other microorganisms in the rumen, intestine, soil, or sewage. All animals, including dogs and cats, ultimately depend on microbially synthesized cobalamin. The chemical structure of the cobalamins consists of two major portions: a planar group with an imperfect resemblance to a porphyrin ring and a nucleotide that lies nearly perpendicular to the planar group. The porphyrin-like moiety contains four reduced pyrrole rings that link to a central cobalt atom (Beck, 2000). While the intestinal flora in cats and dogs can synthesize cobalamins in the presence of cobalt, the site of production in the gut is caudal to the absorptive site. Therefore, the addition of cobalt as a nutrient to dog and cat foods is not warranted.

The major food sources of cobalamin in the diet are animal products, plant products being essentially devoid of the vitamin. In animal and fermentation products, the cobalamin is bound to protein as methylcobalamin or adenosylcobalamin. Before the recognition of cobalamin as a vitamin, the response in performance following the addition of animal versus plant proteins to the diet was called "animal protein factor." Commercially produced cobalamin is derived from fermentation, and during isolation a cyano group is attached. This cyano group is removed in the body after ingestion. Large doses of cobalamin have been used as an antidote for cyanide poisoning. One USP unit of vitamin B_{12} is equivalent to 1 μg of the vitamin. Cyanocobalamin is considered very stable in foodstuffs.

Absorption

The absorption of cobalamins from food requires the presence of glycoproteins called "intrinsic factors" (IFs),

which combine with cobalamins ("extrinsic factor") that are released from foods in the stomach by peptic digestion. Other cobalmin-binding proteins in gastric juice, known as R binders, form complexes with cobalmins that are nonabsorbable. IF is only produced in the gastric mucosa in humans, but its production is weak or absent in the gastric mucosa of dogs and cats (Hippe and Schwartz, 1971; Okuda et al., 1973). In dogs, the pancreas is the major, and the stomach the lesser, source of IF (Batt and Horadagosa, 1989; Batt et al., 1989; Vaillant et al., 1990). The pancreas appears to be the sole source of IF in cats (Fyfe, 1993). The stable cobalamin-IF complex in the small intestine associates with specific mucosal receptors on the microvilli of enterocytes (Levine et al., 1984). IF-cobalmin binds to the receptor in preference to IF alone.

The ileum is generally regarded as the major site of cobalamin absorption in mammals, but significant absorption was shown to occur from the jejunum of cats and dogs (Gazet and McColl, 1967). However, Levine et al. (1984) reported immunoreactive IF-cobalmin receptors only in the ileum of dogs, and Batt et al. (1989) showed much lower binding of purified gastric and pancreatic IF to jejunal than ileal vesicles. After the IF-cobalamin complex binds to the receptor, either cobalamin slowly enters the enterocyte by pinocytosis of the whole complex and dissociation of the cobalamin, or the IF remains outside the cell and only the cobalmin enters. Once in the enterocyte, cobalamin binds to a macromolecule that is immunologically similar to IF.

The plasma and extracellular fluid contain proteins that bind cobalamin. In humans, cobalamin is transported in plasma as methylcobalamin by two proteins: transcobalamin I (also called haptocorrin) and transcobalamin II. Transcobalamin I is a glycoprotein, which is antigenically similar to the R binders present in tissues and tissue fluids of many species, and in humans carries almost all of the total serum cobalamin. Transcobalamin II is a protein composed of two subunits, without a carbohydrate moiety. About three-quarters of the total plasma cobalamin in dogs and cats is associated with transcobalamin II. In cats, cobalamin is mainly in the form of adenosylcobalamin and hydroxocobalamin (Peters et al., 1971; Quadros et al., 1976). Cat and dog plasma does not contain transcobalamin I, but another transport protein, transcobalamin O, which carries about 10 to 15 percent of the cobalamin (Linnel et al., 1979). The erythrocytes of cats unlike humans have higher concentrations of methylcobalamin and hydroxocobalamin than found in plasma (Quadros et al., 1976).

Biological Function

Cobalamin forms two coenzymes, adenosylcobalamin and methylcobalamin, that participate in the functioning of more than a dozen enzyme systems but only two—adenosylcobalamin-dependent methylmalonyl CoA mutase and methylcobalamin-dependent methyltetrahydrofolate-homocysteine methyl transferase (now termed methionine synthase)—are involved in dogs and cats. Adenosylcobalamin-dependent enzymes catalyze carbon skeleton molecular rearrangements, whereas methylcobalamin-dependent enzymes are involved in methyl transfer from a tertiary amine.

Methylmalonyl-CoA mutase participates in the metabolism of propionate, arising from the deamination and degradation of the amino acids and odd-chain fatty acids to succinate. In this reaction, propionyl-CoA is carboxylated by a biotin-containing enzyme to methylmalonyl-CoA. This epimer is then racemized to another epimer that is the substrate for methylmalonyl-CoA mutase, which catalyzes the conversion of methylmalonyl-CoA to succinyl-CoA. When there is a deficiency of methylmalonyl-CoA mutase, there is a reduction in succinate synthesis and methylmalonic acid accumulates in blood and is excreted in the urine.

Methyltetrahydrofolate-homocysteine methyltransferase catalyzes the removal of the N^5-methyl group from N^5-methyltetrahydrofolate and its transfer to homocysteine, producing methionine and tetrahydrofolate. This reaction is of major significance in hematopoiesis (see folic acid).

Dogs

Signs of Deficiency

In contrast to the lack of information on which to base a quantitative requirement, there are a number of clinical reports of cobalamin deficiency in dogs. These reports relate to either deficiencies induced by bacterial overgrowth of the intestine resulting in decreased availability of cobalamin to the dog, or genetic abnormalities of cobalamin metabolism.

Fyfe et al. (1991) reported a selective intestinal malabsorption of cobalamin in giant schnauzers that was inherited as a simple autosomal recessive trait. Affected puppies exhibited inappetence and failure to thrive beginning at 6 to 12 weeks of age, as well as neutropenia with hypersegmentation, anemia, and megaloblastic changes of bone marrow. Serum cobalamin concentrations were low, and methylmalonic aciduria and homocysteinemia were present. Parenteral but not oral administration of cyanocobalamin rapidly eliminated all clinical signs. Oral administration of [^{57}Co]cyanocobalamin with or without IF showed that there was a problem with cobalamin absorption. Transcobalamin II and IF appeared normal, but the receptor for IF-cobalamin was absent from the apical brush border microvilli of the ileum.

Requirements

While dogs have been extensively used as models for the study of cobalamin absorption and transport (see NRC, 1985, for references), there have been no studies on the

quantitative requirements for the vitamin. Arnrich et al. (1952) gave weanling cocker spaniel puppies a semipurified diet containing 20 percent vitamin-free casein for 20 weeks. No anemia was found in the puppies, and while body weight gains were satisfactory, gains appeared to have been increased by a supplement of 50 μg cobalamin·kg^{-1} diet. No measurements of blood concentrations of cobalamin, or urinary excretion of methylmalonic acid were done. Urinary cobalamin excretion has been reported by several investigators (Nelp et al., 1964; Coppi et al., 1970; Silverman, 1979), but no data were presented to allow an estimate of requirements.

In the absence of experimental data, it is suggested that the requirements proposed by NRC (1985) of 7 μg per 1,000 kcal ME be maintained as an adequate intake for all dogs. This dietary concentration is equivalent to a cobalamin intake of 0.92 μg·kg BW$^{-0.75}$·d^{-1} for an adult dog at maintenance. Much higher concentrations would be required for dogs with compromised gastrointestinal function.

Hypervitaminosis

There are no reports of toxicity resulting from ingestion of high doses of cobalamin by dogs. Subcutaneous doses of 2 to 33 μg·kg BW^{-1} have been given to dogs, and have resulted in disturbances of reflex activity.

Cats

Signs of Deficiency

Morris (1977) reported that weaned kittens given a cobalamin-deficient diet grew normally for 3 to 4 months, after which there was a cessation of growth followed by subsequent body weight loss at an accelerating rate until parenteral administration of 10 μg of cyanocobalamin per day was instigated. Following supplementation, there was an immediate gain in body weight. The hair coat of deficient cats had the appearance of being wet. Deficient cats also exhibited elevated basal urinary excretion of methylmalonic acid, which was augmented by a factor of about eight with a valine load. Probably because of the high concentrations of folate in the diet, hemoglobin concentration, hematocrit, and bone marrow histology were normal.

Ruaux et al. (2001) reported that cats with low cobalamin concentrations in serum exhibited elevated concentrations of methylmalonic acid and disturbances in amino acid metabolism indicated by increased concentrations of methionine and decreased concentrations of cystathionine and cysteine.

Clinical cases of cobalamin deficiency in cats have been of two types: those associated with inborn errors and those resulting from bacterial overgrowth of the intestine. Vaden et al. (1992) reported a cat that was anorectic, failed to thrive, and had methylmalonic acidemia and a low serum cobalamin concentration. In an in vitro assay of hepatic methylmalonic-CoA mutase activity, the stimulation from the addition of adenosylcobalamin was greater than in normal animals.

Simpson et al. (2001) reported subnormal concentrations of cobalamin in the plasma of cats exhibiting weight loss, diarrhea, vomiting, anorexia, or thickened intestines. Definitive diagnosis included inflammatory bowel disease, intestinal lymphoma, cholangiohepatitis or cholangitis, and pancreatic inflammation. The authors suggested that cats with subnormal absorption of cobalamin may require parenteral administration of cobalamin every 2 weeks to maintain normal plasma concentrations. The rate of depletion of plasma cobalamin is many times more rapid in cats than in humans where a single injection may be adequate for many months. The difference may be due to defective enterohepatic recirculation of cobalamin in cats or the lack of transcobalamin 1 in plasma.

Requirements

Although the essentiality of dietary cobalamin for weaned kittens given a purified diet has been established (Keesling and Morris, 1975; Morris, 1977), there have been no experiments in which diets containing variable amounts of cobalamin have been given to cats to derive a MR. In purified diets, it is known that 20 μg cobalamin·kg^{-1} (about 4.5 μg per 1,000 kcal ME) will maintain normal hemoglobin concentrations during pregnancy, lactation, and growth of kittens (Kang et al., 1987). Since the bioavailability of cobalamin does not appear to be of significant concern, these concentrations are recommended as adequate intakes for all physiological states.

Hypervitaminosis

There are no reports of toxicity resulting from the ingestion of high doses of cobalamin in cats. Large does of cobalamin have been given as an antidote for cyanide poisoning in species other than cats.

FOLIC ACID

The presence of a factor in foods that prevented megaloblastic anemia and stimulated animal growth was known in the 1930s but was not identified and synthesized until 1946 when it was named folic acid. Originally, it was thought that folic acid was the only factor required for the treatment of pernicious anemia in humans, but with the later discovery of cobalamin it became clear that a second factor was involved. Folic acid (pteroylmonoglutamic acid) consists of a pterin moiety (2-amino-4-hydroxypteridine) linked by a methylene group at carbon 6 to *p*-aminobenzoylglutamic acid. Natural folates occur in the reduced, 7,8-dihydro, and 5,6,7,8-tetrahydro forms. Folates in nature occur as

pteroyloligo-γ-L-glutamates ($PteGlu_n$), where n is 1-9 or more glutamates long (Brody and Shane, 2001).

Absorption, Transport, and Storage

Folate in natural food ingredients is present mainly as pteroylpolyglutamate derivatives that are hydrolyzed in the intestine to monoglutamates by a γ-glutamylhydrolyase (Baugh et al., 1975). Absorption of monoglutamates occurs via a saturable carrier-mediated process, but at high concentrations absorption by diffusion-like processes can occur. The main site of absorption of folates is the jejunum, but some absorption occurs throughout the intestine anterior to the ileum (Bernstein et al., 1972). In the passage across the intestinal mucosa, most of dietary folate is metabolized to 5-methyltetrahydrofolate (5-methyl-$H_4PteGlu_n$), and most of the circulating folate in plasma is in the form of 5-methyl-$H_4PteGlu$. Mammalian tissues do not transport polyglutamates with a chain length of 3 or more. After absorption, folate passes into the portal circulation where much of it is taken up by the liver. In the liver, folates are either released to pass into the circulation or converted to polyglutamate derivatives and retained. The plasma contains low-affinity binding proteins, principally albumin, and high-affinity proteins. Erythrocytes contain higher concentrations of folate than plasma in both dogs (Bunch et al., 1990) and cats (Yu and Morris, 1998). In the tissues, folate is present in both the cytosol and the mitochondria, and accumulates through its conversion to polyglutamates, which do not diffuse out of the cell. The relationship between dietary and serum concentrations of folate in dogs has been reported by Davenport et al. (1994) and in cats by Yu and Morris (1998).

Biological Function

Folates are used as cofactors and serve as donors and acceptors of one-carbon units in a variety of reactions involving amino acids and nucleotide metabolism. These functions of folate result from its ability to transfer one-carbon units as 5-methyl, 5-formyl, 10-formyl, 5,10-methenyl, 5,10-methylene, and 5-formimino groups. The majority of reactions involving folate occur in the cytosol, but folate reactions involving single-carbon transfer between serine and glycine occur in the mitochondria. To be coenzymatically active, the pyrazine ring of the pterin moiety must be reduced to the tetrahydro form and the glutamate chain has to be elongated by addition of glutamate residues. Reactions involving folate can be conveniently grouped into four main categories: amino acid metabolism, nucleotide metabolism, disposal of one-carbon units, and mitochondrial protein synthesis (Brody and Shane, 2001).

In the interconversion of serine to glycine, serine hydroxymethyltransferase catalyzes the transfer of formaldehyde from serine to tetrahydrofolate ($H_4PteGlu_n$) to give glycine and 5,10-methylene-$H_4PteGlu_n$. This reaction occurs in the mitochondria, and the cytosol and is catalyzed by two different isoenzymes. In the mitochondrial glycine cleavage system, glycine in the presence of NAD^+ and $H_4PteGlu_n$ yields carbon dioxide and ammonia, and a single carbon is transferred to $H_4PteGlu_n$ as 5,10-methylene-$H_4PteGlu_n$. A major pathway of single-carbon utilization is the reduction of 5,10-methylene-$H_4PteGlu_n$ to 5-methyl-$H_4PteGlu_n$ by 5,10-methylenetetrahydrofolate reductase and transfer of the methyl group to homocysteine to produce methionine, which regenerates $H_4PteGlu_n$. The methyl transfer reaction is catalyzed by methionine synthetase, a cobalamin-dependent enzyme. Homocysteine is derived from the hydrolysis of *S*-adenosylhomocysteine resulting when a methyl group is donated by *S*-adenosylmethionine.

N-Formiminoglutamic acid is an intermediary in the catabolism of histidine. Formininotransferase catalyzes the transfer of the formimino group to $H_4PteGlu_n$ resulting in the formation of 5-formimino-$H_4PteGlu_n$ and glutamate. This reaction is the basis of a clinical test for folate deficiency. When folate is deficient, the concentration of formiminoglutamic acid (FIGLU) in plasma and urine is greatly augmented especially after a load of histidine.

Folate is not directly involved in the synthesis of pyrimidines but is required for the synthesis of thymidylate. A one-carbon unit at the oxidation level of formaldehyde is donated by 5,10-methylene-$H_4PteGlu_n$ to deoxyuridine monophosphate (dUMP), which results in the production of deoxythymidine monophosplate (dTMP) and the formation of dihydrofolate. This is the only reaction of folate in which the oxidation state changes from tetrahydro- to dihydrofolate and differs from other reactions in that it involves the transfer not only of a hydroxymethyl group but also of a hydride. When folate is not available to perform these functions there is disturbed DNA synthesis and megaloblastic anemia.

In purine synthesis the carbons at positions 2 and 8 of the purine ring are derived from 10-formyl-$H_4PteGlu_n$, which follows from the oxidation of 5,10-methylene-$H_4PteGlu_n$. Folate also participates in the oxidation of one-carbon moieties to carbon dioxide. The enzyme 10-formyl-tetrahydrofolate dehydrogenase catalyzes the oxidation of the 10-formyl group of $H_4PteGlu_n$. A less quantified role of folate is in protein biosynthesis in mitochondria, which is initiated by a special transfer RNA, *N*-formylmethionyl-$tRNA_f^{met}$. The formyl group for this tRNA is donated by 10-formyl-$H_4PteGlu_n$.

Dogs

Signs of Deficiency

Afonsky (1954) reported that a dog given a purified diet for 152 days exhibited body weight loss, a decline in the hemoglobin concentration of blood, and a lowered hemat-

ocrit. A single injection of folic acid normalized hemoglobin and hematocrit within 14 days; thereafter hemoglobin declined, but it returned to normal after a further injection. Sheffy (1964) reported erratic appetite and decreased weight gains in folate-deficient puppies. In an observational study without controls, Elwood and Colquhoun (1997) reported a decrease in the incidence of cleft palates in Boston terrier puppies from 17.6 percent to 4.2 percent following daily supplementation of the bitches with 5 mg folic acid from mating until the pups were 3 weeks of age. Folic acid supplementation of women during pregnancy has been shown to reduce the incidence of neural tube defects (Medical Research Council, 1991).

Requirements

Krehl and Elvehjem (1954) gave dogs a niacin-deficient diet without added folate and reported that they responded poorly to the addition of nicotinic acid. However, when a "folic acid concentrate" from liver was added to the diet, the dogs consistently responded to the addition of nicotinic acid, indicating the essentiality of folic acid for dogs. Folates are produced by bacteria in the gut and are absorbed, but the contribution from this source has not been quantified. Information from other species indicates that the type of diet will affect the amount absorbed. Bernstein et al. (1975) reported that the gut of dogs contained at least four folate compounds including 5-formyl- and 5-methyltetrahydrofolic acid and tetrahydrofolic acid.

Sheffy (1964) depleted 4- to 5-week-old puppies of folate by giving a purified casein-based diet containing sulfasuxidine without added folate. After 9 weeks, the dogs developed erratic appetites and body weight gains decreased, but there was no change in blood hemoglobin concentration. All dogs were then given a vaccination of distemper and infectious hepatitis antigens and divided into two groups. One group received 27.5 μg folic acid·kg BW^{-1}·$d^{-1}$and the other group was not supplemented. Antibodies were found in the supplemented dogs 8 days after challenge, whereas depleted dogs did not show antibodies until 17 days after vaccination. Sheffy suggested that the folic acid requirement was less than 13μg·kg BW^{-1}·d^{-1}.

The folic acid needs of dogs given diets based on natural constituents and not containing bacteriostatic agents may be partially met by microbial synthesis in the intestine. However, diets that are inadequate in choline, methionine, and cobalamin may increase requirements for folic acid.

Following a review of the literature, it is suggested that the folic requirement given by the NRC (1985) of 54 μg per 1,000 kcal ME be retained for all physiological stages. This dietary concentration supplies 7 μg·kg $BW^{-0.75}$·d^{-1} for adult dogs at maintenance and over twice that for growing puppies.

Excess Intake of Folic Acid

No adverse responses to folic acid have been documented (NRC, 1987), but a presumed safe level of 1,000 times the requirement is suggested.

Cats

Signs of Deficiency

Long-term folate deficiency in cats is associated with a decrease in growth rate and an increase in plasma iron concentration (Carvalho da Silva et al., 1955), megaloblastic anemia (Thenen and Rasmussen, 1978; Yu and Morris, 1998), and greatly augmented urinary excretion of FIGLU following an L-histidine load (Yu and Morris, 1998). Yu et al. (1999) reported in addition erythroid hyperplasia of the bone marrow and significant elevation of plasma concentration of homocysteine, the latter being higher in male than female kittens.

Requirements

Carvalho da Silva et al. (1955) was not able to produce folate deficiency in 2- to 3-month-old kittens given a purified diet without added folate or cobalamin unless sulfonamides (sulfaguanidine or sulfanilamide) were added to the diet. Assessment of folate deficiency was based mainly on hematological parameters. Either no or slight hematological responses to low doses of parenteral folate were obtained in kittens receiving the sulfonamide diet without folate. The greatest responses were obtained to supplementation with a combination of folate and cobalamin, indicating that the authors may have produced a multiple deficiency state.

Amyes et al. (1973) reported that the folic acid concentration of cat plasma, erythrocytes, and liver declined from birth to 32 days, but no information was given on the dietary folate concentration. Folate deficiency was produced in weanling kittens given a purified diet based on casein and lard without added folate by Thenen and Rasmussen (1978). The basal diet contained 2 μg folate·kg^{-1} and by 10 weeks the kittens had developed megaloblastic anemia. No evidence of anemia was present in control kittens given the same diet with 1.36 mg folic acid·kg^{-1}.

Yu and Morris (1998) gave 8-week-old weaned kittens a complete purified diet (except for folate) based on gelatin and amino acids. When the kittens were 10 weeks of age, they were given one of seven diets with folic acid concentrations varying from 0.1 to 1.2 mg·kg^{-1} diet. At 20 weeks of age, mean corpuscular volume and mean corpuscular hemoglobin were elevated in groups given diets with less than 0.3 mg folate·kg^{-1}, but all other hematological parameters were unaffected by dietary folate levels. Plasma, erythrocyte, and whole-blood folate levels were linearly related to dietary folate concentration. After a histidine load of 0.22 g of L-his-

tidine·kg BW^{-1}, FIGLU excretion was elevated in kittens receiving diets containing less than 0.6 mg folate·kg^{-1} diet. The authors recommended a minimal concentration of 0.6 mg folic acid·kg^{-1}. For a dietary concentration of 0.6 mg of folic acid·kg^{-1}, the mean concentrations of folate in whole blood, erythrocytes, and plasma were 5.9 ± 1.1, 17.8 ± 2.3, and 3.6 ± 0.3 μg·L^{-1}, respectively.

A concentration of 0.6 mg of folic acid·kg^{-1} diet (of 4 kcal ME·g^{-1}) is equivalent to a folate intake of 15 μg·kg $BW^{-0.67}$·d^{-1} for an adult cat at maintenance.

Excess Folates in the Diet

There are no reports of adverse reactions resulting from the ingestion of excess folate by either cats or dogs. The NRC (1987) stated that "administration of massive doses of folic acid in the diet have not been reported to cause adverse effects."

BIOTIN

The discovery of biotin as an essential nutrient for animals was intimately linked with the demonstration that certain food extracts were able to reverse a condition produced by the feeding of raw egg white. Egg white contains a glycoprotein avidin that very tightly binds biotin (dissociation constant $[K_d] = 10^{-15}$), is resistant to intestinal proteolysis, and is biologically inactive. One molecule of avidin binds four molecules of biotin, and even heat treatment (15 minutes at 100°C) releases only 0 to 10 percent of the bound biotin (Green, 1963). Spontaneous biotin deficiencies rarely occur in dogs and cats in the absence of a diet containing raw egg white. Additionally, biotin is well distributed among foods and microbial synthesis in the gut may provide most if not all of the vitamin requirement (Murthy and Mistry, 1977).

Absorption

Although biotin is widely distributed in foodstuffs, the concentration is low compared to the other water-soluble vitamins. Most of the biotin in foods, including meats and cereal grains, is covalently bound to proteins. The form of the binding is ε-*N*-biotinyl-L-lysine (biocytin). During the luminal phase of digestion, biotinidase in pancreatic juice may release biotin (Wolf et al., 1984), or biotin attached to oligopeptides may be released by mucosal biotinidases. In the intestine of rats, biotin is cleaved from the protein by the enzyme biotinidase. A biotin transporter has been demonstrated in the intestinal brush border membrane and in brush border membrane vesicles. This transporter requires both an intact ureido group and a free carboxyl group on the valeric acid of biotin for active transport (Bowman et al., 1989; McCormick and Zhang, 1993). In biotin deficiency in rats, there is up-regulation of biotin transport by an increase in V_{max}, indicating an increase in number of transporters but no change in affinity. Carrier-mediated transport moves the biotin from the enterocyte across the basolateral membrane. In humans, biotin in plasma is in the free form (Mock and Malik, 1992). No studies have been done on the absorption or transport of biotin in dogs or cats.

A biotin transport system has been identified in vesicles prepared from kidney brush border and basolateral membranes. Since most of the biotin in plasma, at least in humans, is in the free form, an efficient transport system is required to prevent undue loss of biotin from the glomerular filtrate.

No studies were found on the site of absorption of biotin from the intestine of cats or dogs. However, in rats, although maximal transport occurs in the small intestine, absorption from the proximal colon is significant (Bowman and Rosenberg, 1987), supporting the potential contribution of biotin synthesized by enteric microflora. Also, this finding provides a rationale for the need to use dietary sulfonamides to produce biotin deficiency in experimental animals.

The bioavailability of biotin in corn, soybean meal, and meat and bone meal to chickens is high (86 to 100 percent), but in wheat, barley, triticale, and sorghum it is only about 50 percent (Baker, 1995).

Biological Function

Biotin is a bicyclic compound; one of the rings contains a ureido group and the other contains sulfur in a tetrahydrothiophene ring with a valeric acid side chain. Biotin has three asymmetric carbon atoms; hence, there are eight stereoisomers of which only one, *d*-(+)-biotin, which occurs naturally, is enzymatically active (Mock, 2001). Biotin serves as an essential cofactor in four carboxylase reactions in mammals that catalyze the incorporation of bicarbonate as a carboxyl group into substrates. In nonmammalian systems, biotin-dependent enzymes also act as transcarboxylases and decarboxylases.

Three of the four mammalian carboxylases are mitochondrial enzymes (pyruvate, propionyl-CoA, and methylcrotonyl-CoA carboxylases) and the fourth, acetyl-CoA carboxylase, occurs in both mitochondria and cytosol. Pyruvate carboxylase catalyzes the incorporation of bicarbonate into pyruvate to form oxaloacetate, which in gluconeogenic tissues such as liver and kidney can be converted to glucose. Degradation of the amino acids isoleucine, methionine, threonine, and valine results in the production of propionyl-CoA, which on carboxylation (catalyzed by propionyl-CoA carboxylase), is converted to the D-isomer of methylmalonyl-CoA. After several steps, methylmalonyl-CoA is converted to succinyl-CoA, which feeds into the tricarboxylic acid cycle. Methylcrotonyl-CoA carboxylase, the third mitochondrial biotin-dependent carboxylase, is involved in the degradation of the amino acid leucine. Acetyl-CoA carboxylase catalyses the incorporation of bicarbonate into acetyl-CoA to form malonyl-CoA, which is a substrate for fatty acid elongation.

In the carboxylases biotin is attached to the apocarboxylase by a condensation reaction catalyzed by holocarboxylase synthetase, which is present in both cytosol and mitochondria. Attachment occurs via an amide bond formed between the ε-amino group of a lysine residue on the apocarboxylase and the valeric acid carboxylic group of biotin.

Dogs

Signs of Deficiency

There are no reports providing an adequate description of the clinical signs of biotin deficiency in dogs. Greve (1963) reported scurfy skin (due to hyperkeratosis of the superficial and follicular epithelia) and a marked decline in the concentration of urinary biotin. In contrast to cats, alopecia and hypochromotrichia have not been reported in biotin-deficient dogs.

Requirements

A reduction in the activities of pyruvate and propionyl-CoA carboxylases in liver and kidney homogenates from beagle puppies was demonstrated by Shen et al. (1977) in puppies that were fed raw egg white along with a diet without biotin. Greve (1963) gave dogs a diet containing spray-dried egg white and sulfaguanidine to inhibit biotin synthesis by enteric bacteria. These dogs produced urine with a biotin concentration of less than 0.05 $pg \cdot mL^{-1}$ compared to a "normal" of 7 to 13 $pg \cdot mL^{-1}$. While dogs have a metabolic requirement for biotin, a dietary requirement is not likely to be demonstrated when egg white and antimicrobials are not present in a diet of natural foods. ABGE (1989) recommended 2 μg biotin·kg $BW^{-1} \cdot d^{-1}$ for maintenance and 4 μg biotin·kg $BW^{-1} \cdot d^{-1}$ for growth and reproduction.

Hypervitaminosis

There are no reports of biotin toxicity in dogs. Studies in poultry and swine indicate that these species can safely tolerate dietary levels of 4 to 10 times their nutritional requirements for biotin (NRC, 1987). Since biotin is readily excreted in the urine of many animals, the maximal tolerable level of biotin for dogs may be much higher.

Cats

Signs of Deficiency

Clinical signs of biotin deficiency include accumulation of salivary, nasal, and lachrymal secretions, progressive alopecia, achromotrichia, dermatitis, body weight loss, and diarrhea in the terminal stages of the deficiency. Hepatic propionyl-CoA activities are depressed.

Requirements

Carey and Morris (1977) gave 3-month-old kittens a purified basal diet containing 32 percent vitamin-free casein as a protein source. No evidence of biotin deficiency was found when the diet contained no supplemental biotin or when 2 percent succinylsulfathiazole was added to the diet to suppress enteric synthesis. However, when the diet contained 13.5 percent casein and 18.5 percent dried egg white, after 25 weeks the cats had accumulated dried salivary, nasal, and lachrymal secretions in the facial region and developed a progressive alopecia that began at the extremities and progressed over the whole body. Accompanying the alopecia was achromotrichia, a scaly dermatitis, and body weight loss, attended by diarrhea in the terminal stages. Asymptomatic kittens given the 32 percent casein diet without biotin supplementation and 2 percent succinylsulfathiazole were changed to a diet of 32 percent egg white, which was followed by an almost immediate loss of body weight and similar clinical signs. Subcutaneous injection of 0.25 mg D-biotin on alternate days caused remission of clinical signs. There was a marked reduction in the activity of hepatic propionyl-CoA carboxylase in deficient cats, which was restored by parenteral biotin.

Pastoor et al. (1991) reported that a diet containing the same or higher percentage of egg white (18.5 percent) as used by Carey and Morris (1977) produced biotin deficiency in cats. Although these studies demonstrate that cats have a metabolic requirement for biotin, they do not permit an estimate of the requirement. Cats probably do not need a supplemental source of biotin in the diet except under abnormal conditions (e.g., when the diet contains significant amounts of raw egg white). A purified diet containing 60 μg of biotin·kg^{-1} supported pregnancy and lactation in queens and normal growth in kittens. It is suggest that addition of 60 μg biotin·kg^{-1} diet (4 kcal ME·g^{-1}) may be prudent even in the absence of raw egg white in the diet. This dietary concentration will supply approximately 1.5 μg·kg $BW^{-0.67} \cdot d^{-1}$ for an adult cat at maintenance, and this is given as an adequate intake.

Hypervitaminosis

There are no reports of biotin toxicity in cats. Studies in poultry and swine indicate that these species can safely tolerate dietary levels of 4 to 10 times their nutritional requirements for biotin (NRC, 1987). Since biotin is readily excreted in the urine, the maximal tolerable level of biotin for cats may be much higher.

CHOLINE

Choline is not a true vitamin in the classical sense, because many animals are capable of synthesizing choline in the liver by methylation of ethanolamine, using methyl groups donated by *S*-adenosylmethionine. Methylation oc-

curs in two steps and involves two methyltransferases. Because synthesis under some conditions is inadequate, and small amounts of choline in the diet can prevent certain pathological conditions, it has been traditional to include choline with the B vitamins. The need for choline in the diet of dogs was shown coincidental with research on insulin, when it was found that lecithin prevented fatty liver and death in dogs lacking a pancreas (Best and Huntsman, 1932, 1933, 1935). The term "lipotrophic" was applied to choline and other factors that prevented the accumulation of fat in the liver.

Choline is an integral component of the phospholipid phosphatidylcholine or lecithin. The major role of choline is as a donor of methyl groups for methylation reactions. Other compounds including methionine also donate methyl groups, but choline has three methyl groups compared to only one in methionine. Since folic acid and vitamin B_{12} are involved in the transfer of methyl groups, the functions of these three compounds are interrelated. A small fraction of dietary choline is acetylated in cholinergic neurons for acetylcholine synthesis.

Absorption

In foods, choline occurs as free choline and as phosphoesters in phospholipids such as phosphatidylcholine and glycerophosphocholine. Choline is absorbed primarily in the intestine, but little is known about the efficiency of choline absorption since it is degraded by intestinal microflora to trimethylamine. The bioavailability of choline in soybean meal to chicks for growth has been estimated in two studies to range from 60 to 70 percent and from 85 to 90 percent compared to choline chloride (Baker, 1995)

Biological Function

In biological tissues, choline occurs in the free form (trimethylethanolamine) and as phospholipids (lecithin). Choline has three main roles: in phosphatidylcholine, as a methyl donor, and as a component of acetylcholine. Phosphatidylcholine (lecithin) is a structural element in membranes and a required component of VLDLs. The mobilization of triacylglyerol from liver and its delivery to tissues is accomplished mainly by VLDLs, and in choline deficiency the diminished capacity of the liver to synthesize phosphatidylcholine results in the accumulation of lipids.

Platelet-activating factor is a choline-phospholipid, which besides activating platelet aggregation, is involved with changes in vascular permeability, phagocytosis, and glycogenolysis. Choline phospholipids also participate in signal transduction both through amplification of external signals and in the termination of signals by production of inhibitory compounds.

The second major functional role of choline is to provide active methyl groups for methylation reactions. These include the formation of methionine from homocysteine involving the enzyme betaine-homocysteine methyltransferase, which uses the choline metabolite betaine as a methyl donor. The alternative pathway of methionine regeneration from homocysteine uses the enzyme N^5-methyltetrahydrofolate-homocysteine methyltransferase, and the methyl group is supplied by methylcobalamin. A perturbation in the availability of one of the methyl donors results in compensatory changes in the other donor. Other important synthetic reactions involving active methyl groups are the synthesis of creatine from guanidinoacetic acid and synthesis of trimethyllysine for carnitine synthesis. A small fraction of the daily choline need is used for acetylation in cholinergic neurons to produce acetylcholine.

Deficiencies of choline in species other than cats and dogs have been associated with the development of hepatocarcinomas in the absence of a known carcinogen (Newberne and Rogers, 1986). Choline supplementation of rat dams at two critical times in the development of the pup's brain have been shown to increase the ability of offspring to perform visuospatial tasks. The two critical periods coincide with prenatal neurogenesis of cholinergic cells and postnatal development of synaptosomes (Fibiger, 1991).

The interaction between choline and other nutrients was appreciated following demonstration that the choline requirement of rats could be spared by increasing the casein content of the diet (Best and Huntsman, 1935), which Tucker and Eckstein (1937) explained as a response to increased methionine intake. Therefore, dietary requirements for choline are not fixed but will respond to other components of the diet that are potential methyl donors, particularly methionine, and nutrients such as cobalamin and folate that are involved in methyl transfer.

Dogs

Signs of Deficiency

Best and Huntsman (1935) demonstrated that choline deficiency in dogs was associated with a loss of body weight, vomiting, an increase in fat content of the liver, and death. McKibbin et al. (1945) also reported that a choline-deficient diet resulted in decreased food intake and weight gain and accumulation of fat in the liver, as well as reduced hepatic clearance of sulfobromophthalein, an elevation of blood phosphatase, and a decrease in plasma cholesterol and cholesterol esters. Supplementation with choline reversed these clinical signs in 5 to 10 days. Baker et al. (1986) reported that the total choline content of the plasma of 25 dogs had a range of 235 to 800 $mg \cdot L^{-1}$, with a median of 430 $mg \cdot L^{-1}$.

Requirements

Best et al. (1933) reported that two depancreatized dogs weighing 12.6 and 16.7 kg, respectively, were kept in excellent health by a diet supplying 1.5 g or 2.25 g of choline

daily and that the fat content of the liver remained low. Schaefer et al. (1941) stated that a number of workers had found that dietary choline was not required when the diet contained 40 percent or more casein. Schaefer et al. (1941) observed that puppies given a diet of 190 g casein·kg^{-1} failed to grow, but the addition of 50 to 100 mg choline·kg BW^{-1}·d^{-1} resulted in a resumption of body weight gain. Fouts (1943) also reported that puppies given a diet of 150 g casein·kg^{-1} developed fatty livers, but this did not occur when the diet contained 410 g casein·kg^{-1}. Supplementation of the 150-g casein·kg^{-1} diet with 100 mg choline·kg^{-1} gave improved weight gains but did not resolve the accumulation of fat in the liver. Using a diet based on 300 g of extracted peanut meal and 70 g casein·kg^{-1}, McKibbin et al. (1944) showed that without supplementation, weanling puppies died of acute choline deficiency in less than 3 weeks. Supplementation with 7 g DL-methionine or 1 g choline chloride per kilogram of diet rendered it adequate.

There appears to be no new published information on choline requirements of dogs since the NRC (1985) that proposed a choline allowance of 340 mg per 1,000 kcal ME. It is recommended that this dietary concentration be used for all physiological life stages. This dietary concentration of choline will supply approximately 45 mg·kg BW$^{-0.75}$·d^{-1} for an adult dog at maintenance.

Excess Choline in the Diet

Davis (1944a) gave dogs daily oral doses of 5 g of soybean lecithin (about 150 mg of choline), which caused a decrease in circulating erythrocytes that attained a maximum after 12 to 25 days and persisted for at least 10 days after cessation of dosing. Doses of 8 mg choline chloride·kg BW^{-1}·d^{-1} reduced erythrocyte numbers from a mean of about 5.7×10^6 to about 3.5×10^6 per microliter, and there was a similar decline in hemoglobin concentration. The author suggested that choline administration depressed erythropoiesis by increasing the oxygen supply to bone marrow. In further studies on 15 dogs, oral dosing of choline chloride (10 mg choline chloride·kg BW^{-1}) with various frequencies was used (Davis, 1944b). Three daily doses produced a 30 to 43 percent reduction in erythrocytes. In both reports, dogs received a commercial dog chow with rolled oats (proportions not stated). No control dogs given only this diet were used in either study, and, in the latter study, injections of a liver extract or the feeding of a stomach preparation restored red cell numbers, suggesting that the basal diet may have been deficient in an essential nutrient(s).

In contrast to these findings, McKibbin et al. (1944) supplemented the diet of growing puppies with 1,500 mg choline chloride·kg^{-1} and reported no problems. Similarly, McKibbin et al. (1945) successfully used supplements of 2,000 mg·kg^{-1} diet with growing puppies. Concentration of 2,000 mg·kg^{-1} did not affect gain of pigs during the growing and finishing phases, but decreased gain when fed from weaning (Southern et al., 1986). In a review by the NRC (1987) of the tolerance of animals to excess choline in the diet, only the studies of Davis (1944a,b) reported anemia. A presumed safe maximum intake of 2,000 mg choline·kg^{-1}diet is proposed.

The effect of supplemental choline on anion-cation balance of dogs does not appear to have been examined. Since the metabolism of choline chloride results in a nonmetabolizable anion (chloride) that contributes to the total (fixed) acid load, it would be expected to decrease urine pH.

Cats

Signs of Deficiency

At suboptimal concentrations of dietary choline, food intake and body weight gain of growing kittens is depressed (Carvalho da Silva et al., 1959; Anderson et al., 1979; Schaeffer et al., 1982) and there is an accumulation of lipid in the liver. Mansur Guerios and Hoxter (1962) also reported hypoalbuminemia in choline-deficient cats, and while this was also reported by Schaeffer et al. (1982) it may have been a sign of general inanition rather than specific to choline deficiency. Baker et al. (1986) reported that the total choline content of the plasma of 29 cats ranged from 180 to 490 mg·L^{-1} with a median of 300 mg·L^{-1}.

Requirements

Carvalho da Silva et al. (1959) gave young cats a diet that contained 420 g casein and 240 g of hydrogenated coconut fat per kilogram supplemented with 1 g choline·kg^{-1} diet and reported some growth, but with the presence of fatty infiltration in the liver. Increasing the choline to 5 g·kg^{-1} diet improved growth rate and prevented fatty liver.

Anderson et al. (1979) gave young cats an amino acid-based diet containing 4.5 g methionine, 4.5 g cystine, and 250 g turkey fat (no bioavailable choline by chick assay) per kilogram diet. Growth rate was maximized at 1 g of choline·kg^{-1} diet, but in agreement with the previous authors, there was fatty infiltration of the liver at this choline concentration. When the choline concentration was increased to 3 g·kg^{-1} diet, there was a reduction in liver lipids to normal levels. These authors also demonstrated that methionine was an effective methyl donor for cats, and the need for choline in the diet could be totally supplanted by methionine on an isomethyl basis (3.7 g methionine was isomethyl to 1 g choline) when present in excess of its requirement as an amino acid.

The choline requirement of growing kittens was also investigated by Schaeffer et al. (1982), who used a basal diet containing 330 g soy protein (contributing 0.4 g choline) per kilogram. Six levels of choline 0, 1.0, 1.5, 2.0, 2.5, and 3.0 g·kg^{-1} were added to the diet. Body weight gain was maximized with diets containing 2.0 g of added choline. Liver lipids of kittens receiving diets containing from 0 to 2 g added choline·kg^{-1} decreased linearly. The authors concluded that if

choline in the basal diet had a bioavailability of 100 percent the choline requirement of kittens was 2.4 g·kg^{-1} diet.

This choline requirement of 2.4 g·kg^{-1} diet (4.7 kcal ME·g^{-1}) for growing kittens is equivalent to a requirement of 510 mg per 1,000 kcal ME. In the absence of more recent information on the choline requirements of cats it is proposed these dietary concentrations be maintained as a MR for growing kittens and adults cats at maintenance and during pregnancy and lactation. This dietary concentration of choline will supply approximately 45 mg·kg BW$^{-0.67}$·d^{-1} for an adult cat at maintenance.

Excess Choline in the Diet

No information was found on the SUL of choline in cat diets. However, the metabolism of choline chloride provides a nonmetabolizable anion (chloride) that contributes to the total (fixed) acid load the kidneys excrete, which will acidify the urine.

ASCORBIC ACID

Most animals, including dogs and cats are able to synthesize the ascorbic acid they need for normal metabolism from glucose. Only some primates, guinea pigs, some snakes, some fruit-eating bats, and passiformes birds are unable to undertake this synthesis and require ascorbate in the diet. These animals lack the key enzyme L-gulono-γ-lactone oxidase (EC 1.1. 3.8) that oxidizes L-gulonolactone to 2-keto-L-gulonolactone, which spontaneously converts to ascorbic acid. L-Gulonolactone oxidase is located in the kidneys of reptiles and in the liver of mammals that are able to undertake the synthesis.

Biological Function

Ascorbic acid functions as a catalyst in many biological reactions and as a redox cofactor and is involved in the synthesis of a number of hormones and in hormone activation (Johnston et al., 2001). In several of the reactions in which ascorbate is an essential cofactor, ascorbate provides electrons to enzymes that require metal ions (e.g., Fe, Cu) in a reduced form for activity. These reactions are accelerated by ascorbate but do not involve its direct participation. Reactions in this category include the hydroxylation of proline and lysine residues in the synthesis of collagen and elastin and in the synthesis of acetylcholinesterase. Collagen is the predominant structural protein of animals, and for stability the polypeptide chains of fibrillar collagens must have a minimal number of prolines hydroxylated. Ascorbate also appears to stimulate collagen synthesis independent of its role in hydroxylation by stimulation of collagen gene expression (Geesin and Berg, 2001)

In animals that do not synthesize vitamin C, the clinical signs of ascorbate deficiency are collectively known as scurvy. The pathology of the deficiency largely involves the extracellular matrix and is characterized by conditions including capillary fragility, petechial hemorrhages, bleeding and delayed wound healing.

The conversion of dopamine to norepinephrine is catalyzed by dopamine β-hydroxylase, which depends on ascorbate for its action. Dopamine β-hydroxylase is a tetramer containing two Cu ions per monomer. The primary function of ascorbate is to maintain this copper in the reduced state.

Many hormones and hormone-releasing factors must be amidated by a posttranslational step at their carboxyl terminus (C-terminus) to exhibit full activity. Examples of hormone activation include melanotropins, calcitonin, releasing factors for growth hormone, corticotropin and thyrotropin, pro-ACTH (adrenocorticotropic hormone), vasopressin, oxytocin, cholecystokinin, and gastrin (Johnston et al., 2001). Peptidylglycine-α-amidating mono-oxygenase, which is ascorbate-dependent, catalyzes conversion of glycine-extended peptide hormone precursors to their corresponding α-hydroxyglycine derivatives, which is the first step in the C-terminal amidation process.

Ascorbic acid scavenges reactive oxygen and nitrogen species that are involved in the oxidative damage of lipids, proteins, and nucleic acids. These reactive radicals include superoxide and hydroperoxyl radicals, singlet oxygen, ozone, peroxynitrite, nitroxide radical, and hypochlorous acid. Under some experimental systems, ascorbic acid supplementation has been associated with reduced lipid DNA and protein oxidation.

High intake of ascorbic acid may act as a prooxidant and induce lipid peroxidation. The mechanism proposed is through promotion of Fenton reactions, the first step of which involves reduction of Fe^{3+} to Fe^{2+} by ascorbic acid and production of the hydroxyl radical (OH·) from molecular oxygen and ferrous ions (Fe^{2+}). The hydroxyl radical extracts a proton from unsaturated lipid molecules, producing a lipid radical (L·), the first step in the initiation process. These lipid radicals in the presence of oxygen radicals form lipid peroxide radicals (LOO·) that further react with adjacent lipid molecules to form the hydroperoxides (LOOH) and lipid radicals (L·). Since ascorbate enhances decomposition of lipid hydroperoxides to alkoxyl radicals (LO·), ascorbic acid may also participate in the process referred to as propagation (Geesin and Berg, 2001). The prooxidant effects of ascorbate can be reduced by increasing the intake of vitamin E. Chen (1981) gave rats graded levels of all-*rac*-α-tocopherol (50, 60, 100, 200, and 500 IU·kg^{-1} diet), with and without the addition of ascorbate (0 or 1.5 g·kg^{-1} diet). At the end of 1 month, rats receiving the diet of 50 IU vitamin E with 1.5 g ascorbate·kg^{-1} diet had significantly higher erythrocyte (RBC, red blood cell) hemolysis percentages, liver thiobarbarbituric acid reducing substances (TBARS), and reduced glutathione concentrations in RBC. The effect of the ascorbate on these oxidative indices diminished with the level of vitamin E in the diet.

Dogs

Requirements

Innes et al. (1931) demonstrated that unlike guinea pigs, dogs did not require a dietary source of ascorbic acid. Puppies given a diet devoid of ascorbic acid for 147 to 154 days showed no evidence of growth impairment, or lesions of the teeth, although the same diet fed to guinea pigs produced scurvy and death within 25 days. The ability to synthesize ascorbate was shown to be present in the first week of postnatal life. Naismith (1958) took litters of puppies and allocated them to three treatments: remaining on the bitch or given milk replacer with or without ascorbic acid. No differences occurred in blood ascorbate concentration regardless of treatment. The milk of bitches contains about four times the concentration of ascorbate as the blood (Naismith and Pellett, 1960). Chatterjee et al. (1975) reported that the in vitro rate of ascorbic acid synthesis from L-gulono-1,4-lactone by microsomes isolated from the livers of cats and dogs was one-quarter to one-tenth that of a number of other mammals they tested. Reptiles and amphibia tested also have higher rates of ascorbate synthesis in the kidneys than cats and dogs. Whether cats and dogs have a lower in vivo ability to synthesize ascorbate has not been further investigated. In hepatic disease, lower plasma concentrations of ascorbate are present in these animals.

There have been a number of uncontrolled clinical reports purporting to identify either scurvy in dogs or a clinical response to ascorbate supplementation of dogs infected with canine distemper, exhibiting hypertrophic osteodystrophy, hip dysplasia, or other conditions (Garlick, 1946; Meir et al., 1957; Ditchfield and Phillipson, 1960; Holmes, 1962; Hunt, 1962; Sadek, 1962; Bendefy, 1965; Belfield, 1967, 1976; Leveque, 1969; Vaananen and Wikman, 1979). Sheffy (1972) conducted a series of controlled experiments on the protective effect of ascorbate for puppies infected with either canine herpes virus, agents that produced the clinical syndrome of kennel cough, or infectious canine hepatitis. In one of the two herpes virus studies, the mortality was two out of three treated dogs and one out of three of the control dogs. There was no difference in either experiment in the clinical signs or gross or histopathological changes because of ascorbate supplementation. Similarly, there were no differences found in the kennel cough study due to ascorbate treatment. Ascorbate had no effect on the development of clinical signs of illness or convalescence from infection with canine hepatitis virus.

Although supplemental ascorbate has low toxicity and few side effects, caution should be exercised in the amount administered. High intakes of ascorbate have been shown to increase the need for vitamin E to avoid prooxidant effects in rats (Chen, 1981), and it may have similar effects in dogs.

Based on the available evidence, no requirement for ascorbate as a nutrient in the diet of dogs is proposed. Ascorbate may improve the stability of other nutrients in the diet and may have functions associated with protection against oxidative damage.

Cats

Requirements

Addition of ascorbate to the diet has been advocated during periods of stress, such as during showing, breeding, or consumption of high-fat commercial diets (Kronfeld, 1989; Dodds and Donoghue, 1993). However, there is little evidence to support the benefits of this practice. There is a paucity of information on the safety of ascorbate supplementation of cats. Kienzle and Maiwald (1998) reported that daily oral supplementation with 0, 200, 400, and 1,000 mg ascorbic acid resulted in progressive reduction of the urinary pH of cats given a minced beef diet from a mean pH of about 6.9 to 6.5. There was also a dose-dependent reduction in fecal pH. However, when the cats were given a diet of poultry meal (62 percent) and corn starch (24 percent), the effect was even more modest. Doses of 1,000 mg ascorbic acid per day induced diarrhea in some cats. In humans, high intakes of ascorbate were suggested as a predisposing factor for oxalate urolithiasis, but this has not been supported by recent studies (Wandzilak et al., 1994; Auer et al., 1998). Whether high intakes of ascorbate are a risk factor in cats predisposing them to oxalate urolithiasis is unknown.

VITAMIN-LIKE SUBSTANCES

Periodically, since the isolation of the last recognized vitamin (cobalamin) in 1948, claims have been made that certain compounds are essential in the diet and function as vitamins. These claims have not been substantiated. Some claims of essentiality, such as for inositol (an essential nutrient for some bacteria), can be demonstrated at specific stages of development of certain animals. Inositol, like choline, is a constituent of phospholipids, and in inositol deficiency there is an accumulation of lipid in the liver or intestine. Normally, adequate inositol is synthesized from glucose, but very young rats (both male and female) given an inositol-deficient diet accumulate lipid in the liver, which is prevented by inositol supplementation (Anderson and Holub, 1980). Older rats do not accumulate lipid even when fed an inositol-deficient diet. Similarly, female gerbils and hamsters given a diet of coconut oil do not synthesize adequate amounts of inositol (Hegsted et al., 1974; Holub, 1987). Inositol is also involved in signal transduction and phospholipid assembly. No deficiencies of inositol have been documented in either dogs or cats.

The β-oxidation of fatty acids requires that they be transported from the cytosol into the mitochondria. Carnitine plays a carrier role in this transportation by accepting activated fatty acids at the outer membrane of the mitochondria.

Adequate amounts of carnitine are synthesized from peptidyllysine, which is methylated to trimethyllysine, then undergoes an ascorbic acid-dependent hydroxylation and is cleaved from the peptide. Some breeds of dogs have an autosomal recessive defect in the carnitine synthetic pathway, which leads to a deficiency (Katz and Siakotos 1995). These dogs have ceroid lipofuscinoses and dilated cardiomyopathy (Keene et al., 1991b). Supplementation with carnitine in some cases leads to a reduction in clinical signs of the disease. There is no evidence that dogs in a normal domestic environment require carnitine supplementation, nor is there any indication that carnitine is required in the diet of cats.

Other potential compounds are involved in novel biological reactions that range from oxidative deaminations to free-radical redox reactions; these include the orthoquinone family of cofactors: pyrroloquinoline quinone (PQQ), tryptophan tryptophylquinone (TTQ), trihydroxyphenylalanylquinone (TPQ), lysine tyrosylquinone (LTQ), and the copper-complexed cysteinyltyrosyl radical. These compounds, other than PQQ, are covalently linked to the enzyme they serve. TPQ and LTQ are found at the active sites of copper-containing amino oxidases such as diaminooxidase and lysyl oxidase. Other candidates include compounds such as queuosine, coenzyme Q, and pteridines (other than folic acid) such as biopterin. None of these compounds has been shown to be essential in the diet of either dogs or cats.

Queuosine is produced by modification of the nucleoside base queuine and resembles guanidine structurally. Queuosine is preferentially used by some tRNAs and is synthesized through an interaction between the intestinal microbes and the host.

Coenzyme Q (ubiquinone) is a lipophilic substance present mainly in the intermembrane of mitochondria with redox cycling capacity. In the mitochondria, coenzyme Q affects electron transfers through semiquinone intermediates. Structurally, coenzyme Q has similarities to vitamin K in that it is a 2,3-dimethoxy-5-methylbenzoquinone. Coenzyme Q can be synthesized and is readily absorbed from the intestine, which is analogous to the fat-soluble vitamins.

Tetrahydrobiopterin, a pteridine, is an important redox cofactor for phenylalanine hydroxylase. A related compound is the molybdenum pteridine cofactor found in xanthine oxidase that catalyzes the conversion of xanthine to uric acid. In animals, the molybdenum pteridine cofactor is the basis for the essentiality of molybdenum. A similar pteridine cofactor is also involved in sulfur oxidases.

PQQ is an anionic, water-soluble, heat-stable, quinoid compound that is capable of continuous redox recycling (Stites et al., 2000). Under specific conditions (dams deprived of PQQ throughout adult life), PQQ provides a growth stimulus, and it is regarded as an essential nutrient in growing mice given a chemically defined diet (Killgore et al., 1989; Steinberg et al., 1994). While PQQ serves as a cofactor for glucose dehydrogenase and alcohol dehydrogenase in bacteria, no mammalian enzyme has been identified that uses PQQ exclusively as a cofactor. In rat brain neurons, PQQ can generate or scavenge superoxide radical depending on its microenvironment (Zhang and Rosenberg, 2002); it is also neuroprotective.

VITAMIN LOSSES DURING PROCESSING AND STORAGE OF DOG AND CAT FOODS

In contrast to the relatively minor effect of processing on the bioavailability of proteins, carbohydrates, fats, and minerals, processing can have a major effect on the vitamins present in the final diet. This is especially evident for those vitamins that have been added to the diet in pure form or as a concentrate. Although it is not the committee's intention to discuss the formulation and manufacture of commercial petfoods, the potential losses of vitamins that occur during manufacture and storage should be appreciated.

Depending on the vitamin, different approaches have been used to reduce the losses in processing and storage. Changing the chemical form of the vitamin to a more stable compound has been used with some vitamins, for example: thiamin mononitrate in place of the free base, esters (e.g., acetate or palmitate) of retinol and tocopherol in place of the alcohols, and ascorbyl phosphate in place of ascorbic acid. Incorporation of the vitamin in a beadlet is another approach to greater stability and enhances dispersion of the vitamin in the feed mixture. Typically the vitamin is emulsified with gelatin, starch, and glycerol (often with an antioxidant) and sprayed to form beadlets that are subsequently coated with starch. Further treatment of the beadlet, for example, by heat to form a hardened beadlet (often referred to as a cross-linked beadlet) gives further enhanced protection of the vitamin during processing. Cross-linkage may be achieved by inducing a Maillard reaction or by chemical means. The majority of vitamin A used by petfood manufacturers in the United States is in the form of cross-linked beadlets. For many vitamins of the B complex, spray drying is used to enhance stability and form a free-flowing powder.

The inactivation of almost all vitamins that occurs in the preparation of extruded foods and canned foods is directly related to the temperature and duration of the processes and the presence of free metals. Losses on drying and enrobing (adding fat and or digest to the exterior of the dried extruded product) are similarly time and temperature dependent. During storage the moisture content, temperature, pH, and reactive metal ions affect the rate of vitamin loss. Having minerals in less reactive forms such as chelates or present as oxides or carbonates can decrease the loss of many vitamins, compared to when minerals are present as the sulfate or free metals. Iron, copper, and zinc are especially significant in catalyzing Fenton-type reactions and in generating free radicals. Components in the diet capable of scavenging these free radicals reduce vitamin losses. Protection of fat in the diet from peroxidation is an important factor in reducing

TABLE 8-3 Recovery of Vitamins and Carotenoids Added to Extruded Petfoods and Percentage Loss on Storage

Active	Chemical Form	Product Form	% Recovery After Processing			Storage Loss (% per month)
			Typical	Low	High	
Retinol	Retinyl acetate	Cross-linked beadlet	81	63	90	6
		Beadlet	65	40	80	30
Cholecalciferol	Cholecalciferol	Spray-dried beadlet	85	75	90	4
Vitamin E	all-*rac*-α-Tocopheryl acetate	Adsorbate	45	30	85	1
		Spray-dried beadlet	45	30	85	1
	RRR-α-Tocopherol	Oil	40	10	60	10
Vitamin K	Menadione sodium bisulfite complex	Crystalline powder	45	20	65	17
	Menadione nicotinamide bisulfite	Crystalline powder	56	40	75	11
	Menadione dimethylpyrimidinol bisulfite	Crystalline powder	50	30	70	12
Thiamin	Thiamin mononitrate	Crystalline powder	90	30	95	4
	Thiami hydrochloride	Crystalline powder	80	50	85	4
Riboflavin	Riboflavin	Spray-dried beadlet	82	70	90	3
Pyridoxine	Pyridoxine hydrochloride	Crystalline powder	75	70	90	3
D-Pantothenic Acid	D-Calcium pantothenate	Crystalline powder	85	75	95	2
Niacin	Nicotinic acid	Crystalline powder	80	64	90	2
Biotin	Biotin	Spray-dried beadlet	88	60	95	2
Folic Acid	Folic acid	Spray-dried beadlet	90	65	95	<1
Vitamin C	Ascorbyl-2-polyphosphate	Spray-dried beadlet	96	85	100	<1
	Ascorbic acid	Crystalline powder	40	0	60	37
Lutein	Lutein	Spray-dried beadlet	72	50	80	2
Lycopene	Lycopene	Spray-dried beadlet	64	40	75	2
β-Carotene	beta-Carotene	Beadlet	34	20	50	2

SOURCE: Information supplied by J. W. Wilson, Roche Vitamins Inc.

free-radical generation within the diet. Chelating agents such as ethylenediaminetetraacetic acid (EDTA) and phosphoric acid or synthetic antioxidants such as butylated hydroxytoluene and BHTQ added to fat reduce free-radical propagation. As previously indicated, α–tocopherol is an important free-radical scavenger in vivo, and the other tocopherols have lower biological activities. In contrast, in diets, mixed tocopherols (γ and δ) have a greater capacity to scavenge free radicals than α-tocopherol.

Typical, as well as low and high recoveries, of vitamins incurred in the extrusion and drying processes in the manufacture of expanded petfoods and losses in storage are summarized in Table 8-3. Similar and more detailed information on the effect of temperature during extrusion, drying, and storage is also available (Anonymous, 1998). The recoveries of vitamins in these processes vary widely; for some vitamins such as nicotinic acid, recoveries are generally high, whereas for others such as vitamin A they are consistently lower.

Losses of the vitamins during storage of extruded petfoods tend to be higher for fat-soluble vitamins (vitamins A and D_3 in cross-linked beadlets about 8 and 4 percent respectively, per month) than for B vitamins whose losses are of the order of only 2 to 4 percent per month. Thiamin mononitrate and folic acid have the highest rates of loss among the B vitamins (Anonymous, 1998). Data on losses of vitamins during canned storage have not been summarized in the literature.

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9

Water

GENERAL PRINCIPLES

Function

Water is an essential nutrient, but perhaps the least discussed with respect to dietary requirements. Water is most often freely available to dogs and cats and separate from the remainder of the daily ration. Also, when water is provided in ample amounts, healthy dogs and cats can efficiently self-regulate intake to meet their needs. As a result, its contribution to the total diet is largely ignored, and most often it is not considered a critical component of a diet formulation. Despite these facts, its role is vital to the functioning of all living cells.

The functions of water in the body are countless. Water serves as the solvent wherein the vast majority of intra- and extracellular chemical processes occur. It is a major component of most body tissues and fluids. As a principal component of blood, water facilitates the transport of oxygen and nutrients to all parts of the body. It is needed for normal digestion of food, thermoregulation, and excretion of waste in the urine and feces (Case et al., 2000). The gastric emptying time of cats fed a dry diet (5.7 percent moisture) was longer than those fed canned food (75 percent moisture), and the gastric emptying time of cats fed dry diets decreased with increased water intake (Goggin et al., 1998).

Regulation of Intake by Dogs and Cats

In the dog and cat, loss of water occurs primarily as a function of respiration and production of urine and feces. While water losses are continual throughout the day, access to water by terrestrial animals such as dogs and cats is periodic. Thirst is directly correlated with body water content and plasma osmolality, and intake may not be stimulated until a mild degree of dehydration exists (Ramsey and Thrasher, 1991). Intracarotid injections of a small amount of water or larger infusions of water intravenously into dehydrated dogs reduced voluntary consumption, indicating response to both cellular and extracellular dehydration.

The amount of water consumed by dogs was found to be approximately proportional to the deficit of water in the body (Adolph, 1939). Loss of 0.5 percent of body weight (BW) stimulated voluntary consumption in dogs, independent of the time required to achieve that degree of loss (Robinson and Adolph, 1943). The initial consumption of water at this juncture did not wholly restore BW, but was thought to be adequate to restore water content relative to the content of other substances in the body.

In addition to water deprivation, increased losses also stimulate water consumption. Exposure to heat stimulated consumption in dogs, but the timing of consumption was associated with the same degree of water loss observed under normal environmental conditions (Robinson and Adolph, 1943). Access to water during heat application or after a delay did not affect the amount of water consumed.

When exercised on a treadmill, a greater stimulus to drink was observed in dogs offered water immediately after exercise compared to those offered water after a delay of 5-30 minutes (O'Connor, 1975). However, the difference in mean consumption was not statistically significant. In neither case did the dogs drink enough at that time to account wholly for evaporative losses. However, dogs allowed access to water on multiple occasions during the run drank sufficient amounts to meet if not exceed total evaporative losses. Administration of 10-20 mL·kg BW^{-1} by stomach tube before running reduced or abolished drinking but did not cause diuresis. A loss of 0.5-1.0 percent of body water was considered necessary to stimulate drinking by dehydration, the same as in nonexercising dogs either at normal environmental conditions or when exposed to heat. The added stimulus to drink during or immediately after running could not be explained.

Dogs may drink quantities of water sufficient to restore losses within minutes after cessation of water deprivation. Since intake ceases prior to complete gastrointestinal ab-

sorption, factors other than restoration of body water content play a role. Dehydrated dogs with esophageal or gastric fistulae drank volumes consistent with existing deficits and equal to amounts consumed by intact dogs (Adolph, 1943; Ramsay and Thrasher, 1991). Oropharyngeal metering of intake and inhibition of vasopressin secretion serve to limit the risk of overconsumption in the short term (Ramsay and Thrasher, 1991).

The amount and nutrient content of food affects water intake. Given constant food composition, the intake of water is linearly correlated with food intake in dogs (Cizek, 1959). Voluntary water intake is adjusted depending on the moisture content of food by both dogs and cats (Cizek, 1959; Seefeldt and Chapman, 1979). Starvation causes a dramatic decrease in water consumption in dogs, with total intake only one-fifth to one-third of normal (Kleitman, 1927; Gregersen, 1932), although intake gradually increases with prolonged food deprivation (Cizek, 1959). Dehydration occurs in fasted dogs allowed free access to water, although not as severely as in dogs deprived of food and water, or deprived of water but consuming protein in excess of the amount necessary for nitrogen balance (Danowski et al., 1944).

Overfeeding of protein or carbohydrate (but not fat) causes both increased intake and increased retention of water in dogs (Golob et al., 1984). Water intake also increases with increasing dietary protein concentrations in cats (Funaba et al., 1996). High salt (sodium chloride) intake increases voluntary consumption of water in dogs up to fourfold, while salt restriction may reduce water consumption by 20 percent of normal (Cowley et al., 1983).

The act of food intake itself also stimulates the intake of water. Drinking after meal consumption may be stimulated by movement of gastric juice and other fluid into the gastrointestinal tract (Gregersen, 1932). Delay in access to water until several hours after a meal decreases 24-hour intake of water by dogs. In dogs fed once every 24 hours, some preprandial anticipatory drinking may be observed (Ramsay and Thrasher, 1991). Periodic versus continuous feeding of cats resulted in lower daily consumption of both food and water (Finco et al., 1986).

Deficiency in Dogs and Cats

For most nutrients, it may take weeks, months, or sometimes even longer before clinical signs of deficiency become evident. Further, body stores of many substances must be seriously depleted before the situation becomes life threatening. On the other hand, signs of water deficiency can appear within days, and with as little as a 5 percent decrease in body stores (Kirk and Bistner, 1981). Severe health consequences may occur with losses exceeding 10 percent of normal body stores, and death may become imminent with losses approaching 15 percent (Kirk and Bistner, 1981; Hoskins, 1995).

Simple water deficiency can occur in any situation where ample quantities of acceptable water are not available to the dog or cat for an extended period of time (Seigmund and Fraser, 1979). In livestock, water deprivation is also characterized as "salt toxicity," although animals can tolerate large amounts of dietary sodium (up to 13 percent of the diet) provided ample water is available (Buck et al., 1976). Dogs fed up to 4 g·kg BW^{-1}·d^{-1} of salt but allowed free access to water showed no sign of significant salt retention for up to 6 days (Ladd and Raisz, 1949). A dog suffered seizures, hypernatremia, and death following a massive intake of sodium from "salt flour"—finely ground salt (Khanna et al., 1997). Rapid onset of vomiting and progression to clonic-tonic motor activity likely limited voluntary water intake.

Water deficiency most often occurs as a result of poor husbandry, such as when the water supply is interrupted or allowed to become fouled or otherwise undrinkable. Failure to account for an increase in insensible losses (e.g., during heat stress or increased exercise) may be a cause as well. Deficiencies also may occur as a result of disease, either because of decreased intake due to the animal's inability to reach and consume water or because of increased fluid loss due to vomiting, diarrhea, or hemorrhage. These latter conditions also lead to concurrent losses of electrolytes and other substances that may result in various nutritional deficiencies.

The predominant initial clinical sign attributable to pure water deficiency is loss of elasticity of the skin (Seigmund and Fraser, 1979; Kirk and Bistner, 1981). The deficit is shared by all body tissues but early responses are made to help maintain blood volume at the expense of intracellular water. Increased water resorption from feces and urine also helps control losses. Regardless, tissues may become hypertonic, adversely affecting function. Saliva production and appetite may decrease. While this may suppress intake of both water and other nutrients, it may also serve to mitigate insensible losses due to digestion of food and elimination of wastes. As the degree of dehydration increases and the blood eventually becomes less dilute and lower in volume, circulation is impaired, which in turn further affects the function of vital organs such as heart, brain, lungs, and kidneys. In "salt toxicity," neurologic signs may predominate in some species (Buck et al., 1976; Khanna et al., 1997). Death may be due to multiple organ failure.

REQUIREMENTS OF DOGS

Requirements for Maintenance

Water needs can be met by a combination of water consumed voluntarily (free water), water as a component of food (combined water), or water produced endogenously during the metabolism of energy-containing nutrients (metabolic water). The amounts of water produced during the oxidation of proteins, fats, and carbohydrates are approximately 41, 107, and 60 g per 100 g of substrate, respectively

(Rowntree, 1922). In general, 10 to 16 mL of water are produced from the metabolism of each 100 kcal of metabolizable energy (ME) (NRC, 1985).

Several formulas have been used to estimate daily needs for maintenance of normal water balance. The simplest is based solely on body weight and is often used in estimating the needs of animals that are receiving parenteral fluid therapy. The daily water need estimated by this formula is 50-60 $mL \cdot kg\ BW^{-1}$ (Schaer, 1989). This is lower than the findings of English and Filippich (1980), who determined the mean daily water intake of free, combined, and metabolic water for dogs housed indoors at 22-25°C to be 72.9 ± 3.7 $mL \cdot kg\ BW^{-1} \cdot d^{-1}$. However, it is higher than that estimated by O'Connor and Potts (1969), which was only 37.5 $mL \cdot kg\ BW^{-1} \cdot d^{-1}$. The difference between studies may have been caused by higher activity and food intake in the former study. Applying this formula in an example, a 10-kg adult dog would require a minimum of 500 to 600 mL of water per day to account for continuing insensible losses and normal urine output. However, this figure is most useful in circumstances where the animal is sedentary and held in environmentally favorable conditions.

Since water needs appear to be highly associated with amount of food consumed, other formulas that estimate needs based on food intake provide for a broader range of circumstances than one based on body weight. One formula suggests that water intake (milliliters per day) should be double to triple the daily intake (in grams) of dry matter (DM) (Case et al., 2000). The same 10-kg adult dog mentioned above would consume approximately 212 g of dry matter per day by having an average-caloric-density (3,500 kcal $ME \cdot kg^{-1}$ DM) dog food, thus requiring 424-636 mL water per day. Another formula suggests that daily water needs on a milliliter basis are in a 1:1 ratio with energy intake in terms of kilocalories of metabolizable energy per day (Lewis et al., 1987). Based on this formula, the same dog would consume approximately 742 kcal ME per day, using the formula $ME = 132 \cdot kg\ BW^{0.75}$, and hence would need 742 mL water per day as well. Of this amount, approximately 74 to 119 mL would be derived from metabolic water.

The amount of water derived directly from food depends on the type of food. Dry dog food is generally 8 to 10 percent moisture, while canned food often exceeds 75 percent moisture. Therefore, an animal consuming 212 g DM per day would receive only about 21 mL of water from dry food but 636 mL from canned food. The latter amount, combined with the contribution of water from normal metabolism, could meet the dog's minimal daily need for water. Thus, provided no other extenuating circumstances exist, a dog eating only canned food may not voluntarily consume free water.

Requirements for Other Life Stages

Requirements for growth, gestation, and lactation are presumed to be higher than those for adult maintenance, but data are lacking to determine minimum daily needs at these life stages. Since the energy requirements for growth can approach twice maintenance and those of the lactating bitch approach three times maintenance, it is reasonable to presume that water needs increase proportionately. This is especially true for the bitch in heavy lactation, where milk production may depend on ample intake. Thus, estimation of water needs based on caloric intake appears most prudent.

Requirements for Work and Environmental Stress

Requirements for work above that for maintenance obviously depend on the amount of work performed. The evaporative loss of water in sedentary dogs in a kennel at 15-25°C was 0.5 $g \cdot kg\ BW^{-1} \cdot h^{-1}$, while active kennel mates lost 6.7 $g \cdot kg\ BW^{-1} \cdot h^{-1}$ (O'Connor and Potts, 1969). It was estimated that 2 hours of activity doubled the daily loss due to evaporation. Dogs running on a treadmill at up to 10 $km \cdot h^{-1}$ experienced evaporative losses of 2-7 $g \cdot kg\ BW^{-1} \cdot h^{-1}$, compared to 0.8-1.2 $g \cdot kg\ BW^{-1} \cdot h^{-1}$ for dogs standing on the treadmill (O'Connor, 1975). Studies in sled dogs performing long-distance racing in extreme conditions (ambient temperature –10°C to –35°C) showed water turnover of 5.03 $L \cdot d^{-1}$ (190 ± 19 $mL \cdot kg\ BW^{-1} \cdot d^{-1}$), as opposed to 0.91 $L \cdot d^{-1}$ (51 ± 13 $mL \cdot kg\ BW^{-1} \cdot d^{-1}$) for similarly fit dogs that were held in the same environmental conditions but did not participate (Hinchcliff and Reinhart, 1996; Hinchcliff et al., 1997). This is explained as largely due to increased intake of food, with a resulting increased solute load and need for water for urine production and elimination. Presumably, there would be increased losses through respiration and the elimination of feces as well.

Adverse environmental conditions, particularly heat, also can affect minimum requirements (MRs). Dissipation of excess heat from the body is accomplished largely by evaporation of water through panting, although a small amount of loss through perspiration may also contribute. Again, the degree of increased requirements over maintenance depends on the degree of heat stress. A dog walked for 5.8 hours in Boulder City, Nevada (40-42°C), consumed approximately 2.5 times the water than it did when walked for 7.5 hours in Boston at 20-24°C (Dill et al., 1932). Since this study was conducted on a single animal in two different locations where factors in addition to temperature were not considered, strong conclusions cannot be drawn. Regardless, an estimate of the increased water requirement in response to heat derived from a more recent and controlled study on evaporative losses in dogs exposed to various ambient temperatures is approximately 6 $mL \cdot kg\ BW^{-0.75} \cdot d^{-1} \cdot °C^{-1}$ above 30°C (Baker, 1984).

On the other hand, exposure to cold does not appear to affect water requirements. In the aforementioned study on sled dogs in extreme cold (ambient temperature of –10°C to –35°C), dogs under racing conditions consumed more than 10,600 kcal ME per day, or 440 kcal $ME \cdot kg\ BW^{-1} \cdot d^{-1}$

(Hinchcliff and Reinhart, 1996). Since they consumed only 190 mL·kg $BW^{-1}·d^{-1}$ of water, the water-to-calorie ratio is only 0.41, far short of the 1:1 ratio normally assumed to be required. However, the water-to-calorie ratio of dogs held in the same environment that did not participate was also low, only 0.49 (51 mL·kg $BW^{-1}·d^{-1}$ of water and 104 kcal ME·kg $BW^{-1}·d^{-1}$). The authors report the energy needs of untrained sled dogs held in a thermoneutral environment to be 55 kcal ME·kg $BW^{-1}·d^{-1}$. The water intake of these dogs was not reported, but if the 1:1 ratio held true they would consume amounts very close to those reported for the sedentary dogs held in colder conditions. Hence, while the excess calories consumed in response to work increased water consumption proportionally, the increase in calorie consumption in response to cold did not.

REQUIREMENTS OF CATS

Requirements for Maintenance and Other Life Stages

As fundamentally desert animals, cats have developed adaptations to accommodate periods of water unavailability. Their greater ability to concentrate urine than dogs, humans, and many other species allows them to mitigate insensible losses. Cats also appear to be able to tolerate dehydration better than most species (NRC, 1986). As a result, the requirement for water may be lower for cats than for dogs. Studies on water intake in cats did not report caloric densities of experimental diets, but based on dry matter intake data and rough estimates of caloric content of commercial dry foods, the water-to-calorie ratio (counting free and combined water, but not metabolic water) was approximately 0.6 (Seefeldt and Chapman, 1978; Finco et al., 1986). Including an estimate for metabolic water increased the ratio to approximately 0.7. The water-to-calorie ratio for cats on commercial canned food was somewhat higher, approximately 0.9 (1.0 when the estimate for metabolic water is included), but since cats did not show adverse effects at lower ratios this may reflect a relative diuresis. The same calculations used to estimate water needs for maintenance in dogs also can be applied to cats, with the understanding that they may have a greater tendency to overestimate true needs, and individual healthy cats may consume much less than calculated.

There are no data to suggest that the proportional increase in needs above maintenance to accommodate growth, gestation, and lactation would be much different for cats than for dogs. The exception may be when comparing lactating animals, wherein the average litter size of some breeds of dogs (and hence the need for milk production) would be much greater than that for cats.

Finally, it is rare for cats to be held in as extreme environmental conditions as some dogs are, and even rarer for them to be expected to perform prolonged or vigorous exercise. Therefore, the effects of these factors are less of a consideration for cats than for dogs. An estimate of the increased water requirement in response to heat derived from studies on evaporative losses in cats exposed to various ambient temperatures is approximately 8-12 mL·kg $BW^{-0.67}·d^{-1}·°C^{-1}$ above 35°C (Adams et al., 1970; Doris and Baker, 1981). Thus, cats kept outdoors continuously in very warm climates may have increased needs.

Water and Feline Lower Urinary Tract Health

The ability to concentrate urine may also be a contributing factor in some aspects of lower urinary tract health in the cat (Wills and Simpson, 1994; Case et al., 2000). The degree of urine concentration of minerals relative to their saturation points may affect their propensity to crystallize and fall out of solution. Although other factors may play a large role in the process (e.g., urine pH), ensuring water intake adequate to prevent undue urine concentration appears prudent.

Epidemiological studies have implicated dry cat food as a risk factor for feline lower urinary tract disease (Walker et al., 1977). Some studies suggest that cats consuming dry foods did not voluntarily consume enough water to match the total intake of cats offered canned foods, while others have shown no differences (Seefeldt and Chapman, 1979; Anderson, 1982). In the latter case, although body water content and turnover were not affected, cats fed dry food still consumed less water per gram of dry matter intake. Another study in cats showed an increase in mean urine volume (from 63 to 112 $mL·d^{-1}$) when the moisture content of food was increased from 10 to 75 percent, respectively (Gaskell, 1985). Thus, consumption of canned food may cause a relative diuresis (rather than dry food resulting in inadequate intake), although there are no known adverse effects from this excess consumption.

Differences in water intake due to diet type may be the result of factors other than simply the amount of moisture in food. For example, higher protein and/or mineral content of food may increase the solute load and subsequent degree of water consumption and urine production (Wills and Simpson, 1994; Funaba et al., 1996). Because of the increased caloric density of higher-fat foods, total dry matter intake may be lower; hence the total solute load and subsequent need for water may be reduced (Thrall and Miller, 1976). Fecal DM and fecal water intake were also lower, and hence urinary output greater, for cats fed high-fat diets. The amount and type of dietary carbohydrate also may affect fecal losses.

RECOMMENDED ALLOWANCES

Although calculations can be performed to estimate minimal water requirements for dogs and cats, they should not be relied upon in most practical situations. Rather, the animal should be allowed to self-regulate its intake except for extreme circumstances such as severe dehydration or prolonged exercise (see discussion of toxicity, below). Thus, re-

gardless of species, life stage, environmental conditions, amount of work, diet type, or moisture content, the most sensible practice is to provide water free-choice at all times. However, if discrete amounts of water must be transported to a site where the animal is housed, a calculation of requirements may be necessary. The 1:1 water:ME calorie ratio works well in most circumstances, with additional needs in cases of high ambient temperatures. Provision of approximately two times the estimated requirement for the given life stage and expected environment and work conditions of the animal is sensible, so that all contingencies are covered and the animal can freely regulate intake.

Title 9 of the Code of Federal Regulations dictates access to water for a minimum of two 1-hour periods per day for dogs and cats under laboratory conditions (9 CFR 3.10). Regardless, one should strive to come as close to free-choice as possible (e.g., access to water as often and as long as practical). In any case, efforts should be made to ensure that the water remains suitable for drinking whenever it is accessible to the animal. Minimal standards for potability of water for human consumption and appropriate sanitation of water receptacles are desirable and required by law for laboratory animals (9 CFR 3.10).

Water intake will vary considerably depending on conditions and diet type. Under some circumstances, the animal, especially the cat, may appear to drink very little water voluntarily. If the animal is healthy, water intake can be encouraged by keeping it fresh and cool. Cats also may respond favorably to constantly moving water. Increased dietary sodium consumption or addition of flavoring agents to water increase water intake, but these measures should not be necessary in healthy animals (Case et al., 2000; Osborne et al., 2000).

TOXICITY IN DOGS AND CATS

Although dogs and cats generally self-regulate consumption of water, rapid, excessive consumption may occur in extremely thirsty animals. This is most likely to occur after an extended period of water deprivation, vigorous exercise, or prolonged heat exposure sufficient to cause intracellular dehydration (Blood et al., 1979). Subsequent rapid rehydration can cause increased turgor or disruption of cells, particularly of the brain. Therefore, most signs of intoxication are related to the nervous system, such as ataxia, restlessness, seizures, and coma. Lysis of erythrocytes also may occur, causing hemolytic anemia and hemoglobinuria.

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10

Special Considerations for Laboratory Animals

The vast majority of studies used in determining the nutrient requirements of dogs and cats as house pets were conducted on animals kept under laboratory conditions. If anything, the more uniform environmental conditions under which laboratory animals are kept might minimize the degree of variability in requirements compared to the wide range of circumstances to which pets may be subject. Hence, the nutrient requirement recommendations for dogs and cats set forth in this publication are just as valid, if not more so, for animals kept under laboratory conditions as for those kept in households. Regardless, proper diet is of utmost importance to the success of any animal study. Thus, investigators must take special care to ensure that the diet is nutritionally appropriate and that the feeding management is sound.

REQUIREMENTS

Energy

It may initially be presumed that the caloric needs of the dog or cat in the laboratory could be lower than those under more free-roaming living conditions, but this is not the case. As in all dogs and cats, energy requirements depend on housing and environmental conditions. Animals housed indoors, in cages or other limited-size housing, or individually, may be expected to have lower requirements than those that are group-housed, in runs, or exposed to the weather. Under Title 9 of the Code of Federal Regulations, dogs housed in smaller cages must be afforded exercise at least once daily unless this conflicts with experimental protocol (9 CFR 3.8). Regardless, even under the most restrictive situations, laboratory dogs appear to expend energy meeting or surpassing that of the average sedentary house pet (Wichert et al., 1999; Cottrell et al., 2000; Parkman et al., 2000). Therefore, in most cases the daily metabolizable energy needs of the adult, nonreproducing dog in a kennel or other laboratory setting would be estimated best by calculations designed for the "moderately active" animal (132 kcal·kg $BW^{0.75}$). The estimated energy needs of the laboratory cat more closely approximate those of a household cat.

Nutrients Other Than Energy

Other than a possible increase in energy needs, there is a lack of data to suggest that the nutrient requirements for laboratory dogs and cats differ from those of animals in household situations. Increases in intake requirements for nutrients associated with increased energy needs (e.g., B vitamins) may be anticipated, but these should be met by the increased food consumption necessary to meet such needs. Thus, no special considerations for laboratory dogs and cats for nutrients other than energy are recommended.

FOOD SELECTION

General

Choosing the appropriate diet for animals in a study can be a major consideration. In studies that are not intended to look at specific nutritional questions or to include nutritional components, diets fed to dogs and cats most often should be "complete and balanced," (i.e., provide adequate quantities of all known essential nutrients to meet recommended allowances for the appropriate life stages). In these cases, the choice of diets is vast, since the majority of the commercial dog and cat foods sold in the United States will meet this burden and are suitable for use in experimental studies.

Notwithstanding a manufacturer's assurance and documentation that a "complete and balanced" food meets nutrient requirement recommendations set forth in this publication, there are also regulatory standards by which to determine the suitability of a diet for dogs and cats. For commercial products in the United States, manufacturers of a food intended to serve as the sole source of nutrition must substantiate the nutritional adequacy of the product by

methods dictated by the Association of American Feed Control Officials (AAFCO). This organization is an advisory body comprised of representatives from state, federal, and foreign regulatory agencies authorized to regulate the safety and labeling of animal feeds. Under AAFCO, substantiation of nutritional adequacy can be achieved either by formulation to meet minimal and maximal nutrient levels as prescribed in the AAFCO Dog and Cat Food Nutrient Profiles or by successful passage of animal feeding trials following AAFCO testing protocols. Also, foods that are "nutritionally similar" to a food that successfully passed the feeding trial may be considered members of a "product family." Foods meeting the product family membership criteria need not be tested by feeding trials in order to substantiate nutritional adequacy under AAFCO procedures. (AAFCO, 2003).

A food that is formulated to meet AAFCO nutrient profiles must contain specified minimal and maximal levels of essential nutrients such as amino acids, vitamins, and minerals (AAFCO, 2003). Two minimal nutrient profiles exist for both dogs and cats, one for adult maintenance and the other for growth and reproduction (gestation and lactation). Maximal allowed levels of some nutrients apply to both the maintenance and the growth-reproduction profiles. Thus, foods that meet the growth-reproduction profiles meet the maintenance profiles by default, hence qualifying for an "all life stages" designation.

Levels stipulated in the AAFCO profiles were established largely by reliance on recommendations of previous National Research Council (1985, 1986) publications for these species. Adjustments were made in the levels of some nutrients as suggested by the expert panel to account for differences in bioavailability of commonly used ingredients and in response to other practical considerations (Dzanis, 1994). Although the AAFCO profiles may be described as "requirements" (the levels are required to be met by the food if it is substantiated by this means), in this context the AAFCO profiles are similar to nutrient "allowances," rather than "requirements," as the terms are used in this publication.

Under the feeding trial means of substantiating nutritional adequacy, diets are offered as the sole source of nutrition (except water) to a minimum number of animals for a prescribed period of time (AAFCO, 2003). Animals must perform compared to established norms or to a suitable control group in factors such as growth or weight maintenance, critical hematologic and biochemical parameters, and other factors depending on the intended life-stage designation (maintenance, growth, or gestation-lactation). In addition, animals must be examined by a veterinarian at the end of the test, with clinical observations recorded. Failure of a group or individual to meet the specific interpretive criteria, or a finding of clinical or pathological signs of nutritional deficiency or excess upon physical examination of any individual animal, is sufficient to fail the test diet.

Foods that pass gestation-lactation or growth trials are presumed adequate to meet the less rigorous needs of the adult at maintenance by default. To be designated for all life stages, the diet must pass both a gestation-lactation trial and a growth trial using the offspring of the initial test bitches or queens. Products substantiated by this method are not required to meet the AAFCO profiles.

Both methods provide reasonable assurances that the commercial product will perform as expected in providing adequate nutrition. Neither is perfect however, and both have their pros and cons. The nutrient profile formulation method, for example, is conducted on paper and cannot wholly account for factors such as bioavailability of nutrients in all possible ingredients and matrices (Morris and Rogers, 1994). Without actual test feeding of the food, it may not be known if the combination of ingredients in the formula was unpalatable to animals or if the food had any other unanticipated adverse effects (e.g., gastrointestinal intolerance). The animal testing method is far superior with regard to assessment of bioavailability and performance factors. On the other hand, the testing method is less easy for regulators to verify, since they cannot independently validate the results through laboratory analysis as they can with products that meet the AAFCO nutrient profile criteria. Rather, regulatory officials must rely on the competence and integrity of persons attesting to successful passage of the feeding trial, so misinterpretation of results or conflicts of interest cannot easily be assessed. Results of feeding trials also may be adversely influenced by the pre-test status of the animals placed on the diet. For example, a maintenance trial conducted on animals fed a diet containing inadequate amounts of vitamin A may not show clinical evidence of deficiency over the course of the study if the pre-test diet allowed for ample stores of the nutrient. However, the greatest potential drawback of the feeding trial method is the exception for products that are considered members of a product family, which may bear a feeding test label statement but are never directly tested.

A product family is a group of products that are all nutritionally similar to the "lead member," which has been subject to the testing described above. To be deemed similar, the product must be of the same processing type and moisture category (e.g., dry, canned), be close in metabolizable energy content (±7.5 percent), contain key nutrients at levels that meet those in the lead, and meet the levels of other nutrients in either the lead or the AAFCO profiles, whichever is lower (AAFCO, 2003). There are no requirements that similar ingredients be used. Thus, since the lead is not itself required to meet the profiles, the levels of some nutrients may be lower than the amounts stipulated in the profiles for all members as well. Although the profiles attempt to account for differences in bioavailability in potential ingredients, the family method of substantiation does not.

While a tested product does not have to meet the profiles, in most cases it will. Also, reputable manufacturers will not alter ingredient composition in a manner that adversely affects bioavailability, at least not intentionally. Still, it may

not be evident from labeling whether a product was the lead member or not. Thus, it would be most prudent to obtain confirmation that the product has both been formulated to meet the AAFCO Dog or Cat Food Nutrient Profiles and passed the appropriate feeding trials.

Certified Diets

"Certified" is a common term used in the marketing of diets intended for laboratory animals, but it has no regulatory meaning. It does imply that the diet has been subject to additional laboratory analysis to confirm the level of a substance or substances in the diet on a batch-by-batch basis. Much of the cost associated with certified over noncertified diets is related to the fact that diets are not released until conformational analysis is complete. Samples of each batch are also held in storage in case reanalysis is indicated at a latter date.

The statement that a product is certified most often refers to the fact that the levels of potential contaminants meet specified maxima. While this may have no effect on the nutritional adequacy or safety of the diet above or beyond that required for all dog and cat foods, it may be important with respect to measurement of a particular study parameter. For example, some contaminants may affect hepatic enzymes and/or alter drug metabolism, even at levels far below any practical safety consideration (National Research Council, 1996). Presence of a substance in the food also may be contraindicated by the goal of the study or by use of special laboratory subjects (e.g., specific-pathogen free animals).

In addition to certification of potential contaminant concentrations, a manufacturer—upon request—may also be willing to certify that the concentrations of a given nutrient or nutrients are constrained to specified ranges. Use of a diet that is certified by this means may be helpful in controlling nutrient variables that are important to the study, a factor that can be especially important during long-term or sequential studies where food must be purchased on multiple occasions.

Purified and Chemically Defined Diets

When stricter control of nutrient composition is mandated by experimental protocol, a purified or chemically defined diet may be required. These diets are formulated with increasingly pure, invariant, and limited number of ingredients compared to most general or certified commercial formulations. For example, casein or soy protein isolate may be used in place of meat or poultry meals as the primary source of protein in the diet, the latter being more variable in the levels of protein and amino acids than the former and also containing other nutrients such as fats and minerals at higher and more variable levels. In the extreme case of chemically defined diets, the most elemental ingredients are used, such as individual crystalline amino acids in lieu of a "protein" source.

Use of these types of diets offers distinct advantages, especially in the conduct of experiments related to nutritional requirements. It allows the investigator to confidently restrict the level of a particular nutrient to a very narrow range or even to eliminate it from the diet completely if needed. Other potential advantages include more consistent batch-to-batch formulation and less potential for the presence of contaminants to affect study results (Lichtman et al., 1999). Negative aspects include increasing cost of ingredients, poorer animal acceptance, and, depending on the form of the diet (many may be in powder form), increased wastage and difficulty in obtaining accurate intake measurements. Also, use of highly purified formulas may inadvertently limit intake of a number of nutrients that have yet to be established as essential but nevertheless play a role in the normal structure and function of the body (e.g., ultra-trace minerals). Therefore, the degree of purity of a diet should depend on its absolute importance to the integrity of the study.

Examples of use of purified diets in dogs and cats can be found in the literature. Early diets were based on similar formulas developed for rodents, although modified to contain increased animal source protein (Carvalho da Silva, 1950; Allison et al., 1956). Later studies also added nutrients known to be uniquely required by the cat (Piechota et al., 1995).

A significant problem with purified diets is their acceptability by the animal. The source and amounts of fat have been shown to affect consumption rates, and some fats can even cause feed aversion. Bleached tallow was found to be preferred by cats over both butter and chicken fat, but there was no significant difference between the preference for bleached tallow over unbleached tallow, lard, yellow grease, or partially hydrogenated vegetable oil (Kane et al., 1981a). The same study found that cats preferred a diet containing 25 percent yellow grease over diets containing either 10 or 50 percent. Cats also showed a notable aversion to diets containing medium-chain triglycerides (MCTs) (MacDonald et al., 1984). In fact, cats preferred fat-free diets over those containing hydrogenated coconut oil. The reason appears to be related directly to palatability of the diet and not an effect of MCTs on physiology. Addition of safflower seed oil improved, but did not totally ameliorate, decreased consumption rates when cats were fed MCT-containing diets. Cats rejected diets containing as little as 0.1 percent caprylic acid, an eight-carbon MCT (8:0).

Foods for Specific Dietary Purposes (e.g., Medical Foods)

Use of laboratory dogs or cats as models for certain animal or human diseases may dictate the need to modify nutrient composition compared to foods intended for healthy animals. For example, lower levels of protein and phosphorus in diets intended for animals with compromised renal function may help mitigate clinical manifestations of the disease and provide for a more normal quality of life (Allen

et al., 2000). Similar restrictions on other nutrient components may ameliorate signs of other disease processes, such as sodium in cardiac insufficiency and copper in breed-associated liver storage disease.

This is not to say that the levels of these restricted nutrients are necessarily below that required to meet the needs of the healthy animal. Rather, because of the nutrient content of commonly used ingredients, the typical levels of these substances may be well above those that are absolutely necessary for normal nutrition. Lowering these levels closer to the minimum requirements helps alleviate signs of disease but should not in most cases compromise nutritional adequacy.

Commercial diets intended for medical use are held to the same nutritional standards as any other dog or cat foods (AAFCO, 2003). Products that are not "complete and balanced" must indicate that they are "intended for intermittent or supplemental feeding only." Product labels or specifications bearing this statement should not be presumed to be adequate for long-term use.

Special considerations also apply to the postoperative laboratory animal. Feeding these animals may necessitate use of a more palatable and/or nutrient-dense food to encourage adequate consumption. Inadequate intake of nutrients can affect both immunocompetence and tissue repair, compromising surgical recovery. Also, trauma from the procedure may result in a catabolic state, which could at least be ameliorated partially by increased energy and other nutrient intakes (Remillard et al., 2000). In extreme conditions of anorexia or where the procedure itself limits voluntary consumption, use of a complete-and-balanced liquid or gel-form dog or cat product that can be lapped up or delivered by a feeding tube may be necessary. Although the gastrointestinal tract is always the preferred route of administration, parenteral nutrition may be necessary on a temporary basis when the surgery or other experimental procedure compromises gut function.

FEEDING MANAGEMENT

Life-Stage Designation of Food

In cases where the colony contains animals of different life stages (e.g., breeding colonies) and where the intended studies are not nutritional in nature, a single food substantiated to be nutritionally adequate for "all life stages" may be appropriate for the entire colony. This eliminates at least one source of variability among subjects, eases transition of individuals into and out of studies or reassignment to another part of the colony, mitigates potential mistakes in feeding, and reduces inventory problems. Although a diet so designated may provide nutrients in excess of those required for maintenance, it should do no harm and will not appreciably affect total feeding costs when considered in terms of its potential benefits to colony management. Control of energy intake among the various life stages can be achieved by adjustment in amounts and frequency of feeding. As opposed to a breeding colony, a colony of mature, nonreproducing animals may be offered a single food designated for adult maintenance only without undue effect.

Preferences or needs of individuals within the colony may dictate the availability of additional diets. This can be especially true for individuals recovering from surgery or other procedures, or when a medical condition dictates a special-use food. This should be kept to a minimum, however, and animals should be acclimated to the standard colony diet when indicated. Custom-made or specific commercial diets other than the standard colony diet also may be required in some studies, particularly those that examine a nutritional issue. For either individuals or groups, diets should be changed slowly, with an increasing proportion of the old diet being replaced by the new over a few days to a week. This mitigates the potential for food refusal or gastrointestinal intolerance to a new food, as well as overconsumption of a novel diet. The change should be instituted well before initiation of the study.

Form of Food

Most commercial diets are available in dry (10 percent moisture) or canned (75 percent moisture) form. Both are held to the same regulatory standards for safety and nutritional adequacy. However, canned foods tend to contain more animal source ingredients than dry, meaning that protein and fat contents are higher and carbohydrate and fiber contents lower on a dry-matter basis. Canned foods also tend to be more variable in fat (and hence calorie) content between production batches because of natural variability in meat sources. Semimoist foods (30 percent moisture) offer no nutritional advantage to either of the other forms. Regardless, the popularity and hence availability of semimoist foods has declined precipitously over the past decade or so.

Under most laboratory conditions, dry food is the most convenient and practical form. More precise and consistent feeding amounts can be offered, and the food can be left with the animal for more extended periods of time with less risk of spoilage, contamination, or insect invasion. It is also easier to weigh back orts and there is less risk for errors due to moisture loss over time.

Amount Fed

Amounts of food offered to individual or groups of animals at the initiation of a study should be based on calorie estimates of the food and energy requirements of the animals based on life stages, body weights, and conditions under which they are housed. However, a significant degree of individual animal variation should be expected, and some animals may require much more or much less than calculated. Amounts offered to each individual should be adjusted weekly as needed to maintain appropriate body weight and

condition of the animal. The proportion of the daily allotment of food not consumed by the animal may also provide clues as to whether an individual has been provided too much or too little food to meet its needs.

Frequency of Feeding

Dogs should be offered fresh food at least once daily, as required by law (9 CFR 3.9). Dogs tend to gulp food, and in most cases a nonreproducing adult can consume its required caloric intake at a single sitting. This may not be true for the growing puppy and gestating or lactating bitch, however. Regardless, multiple daily feedings may help alleviate boredom and reduce the risk of gastric dilatation-volvulus in susceptible breeds (Bataller, 1995). On the other hand, free-choice feeding could result in excess consumption and weight gain, increasing the risk of developmental bone disease in growing large- and giant-breed dogs and obesity in adults (Kendall and Burger, 1980; Kealy et al., 1992).

Compared to dogs, cats prefer frequent, small meals throughout the day and night (Kane et al., 1981b). Therefore, dry food offered free-choice is the most practical means of feeding. Again, fresh food should be offered daily to mitigate the risk that spoilage or contamination will hinder normal consumption. Many pet cat owners provide free-choice dry food with one or two additional small meals of canned food. However, this is not necessary and is often impractical in a laboratory setting.

Storage of Food

The enemies of dry food are oxygen, light, heat, and moisture. Thus, keeping the diet in opaque, airtight containers and under cool and dry conditions (in no case, at temperatures or humidity above normal indoor comfort levels) is essential to long-term storage. In the same vein, measures should be taken to prevent potential contamination by bird, rodent, or insect infestations. Diets should be stored apart from any drugs, pesticides, or other potential contaminants.

As dry food exits the extruder, it has reached temperatures sufficient to destroy pathogenic organisms (Miller and Cullor, 2000). However, since it may be in contact with nonsterile equipment or materials prior to packaging, it may not remain microorganism-free even in an unopened bag. Although the risk of pathogenic organisms from this source is low, it is possible. Regardless, although most animals normally tolerate small doses of even pathogenic microorganisms, this may be contraindicated in circumstances where potential exposure has to be limited (e.g., specific pathogen-free colonies).

Most instances of microbial contamination are the result of recontamination after processing. A small degree of contamination may present a potential problem only if the conditions provide for microbial growth (e.g., moisture, heat). This emphasizes the need for appropriate storage of food as described above, as well as proper handling of food and sanitation of utensils and facilities.

Sterilization of dry diets at the site of use is unnecessarily extreme in most cases, but may be indicated in the case of specific pathogen-free and especially germ-free animals. Dry diets can be autoclaved or exposed to irradiation to achieve sterility, but only after additional consideration has been given in formulating diets to potential nutrient losses due to the sterilization procedures. The degree of nutrient losses may depend on the times, temperatures, or radiation doses; the quantity and volume of food sterilized in each batch; the lability of specific nutrients; and the particular nutrient matrix of the diet, so manufacturers of both the food and the sterilizing equipment should be consulted before such measures are attempted. Also, although nutrients that are generally synthesized by gut flora in the normal animal (e.g., biotin, vitamin K) are typically added to most commercial petfoods as "insurance," further attention must be given to the adequate provision of these substances in diets intended for germ-free colonies. Unlike the use in food of a chemical antimicrobial agent that retains its function for some time after application, a diet that has been autoclaved or irradiated is immediately susceptible to recontamination. Thus, due diligence should be exercised to ensure that foods treated by either of the latter methods are not exposed to potential contaminants (e.g., treated in closed containers not opened until time of feeding).

Because canned food is sterile and hermetically sealed, little effort is needed for it to retain its wholesomeness and nutritive value. Extreme temperature conditions (especially freezing) should be avoided, as should rough handling or any other action that might dent or rupture the cans. Once canned food has been opened, of course, the risk of contamination with potentially pathogenic organisms greatly increases, indicating the need for the same degree of sanitation as with any other food.

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11

Physical Activity and Environment

INTRODUCTION

Other chapters have considered energy and nutrient intakes for dogs and cats undertaking average amounts of activity in a thermoneutral environment. The purpose of this chapter is to examine how changes in activity or environment affect energy and nutrient intakes required for optimal health and performance.

The relationship between exercise and diet in dogs has been the subject of several recent reviews (Grandjean and Paragon, 1992, 1993a,b; Kronfeld et al., 1994; Hill, 1998; Bontuimpo and Brioschi, 1999; Toll and Reynolds, 2002). Most studies have used trained animals (sexually intact male and female sled dogs, greyhounds, beagles, foxhounds, or mixed-breed dogs weighing 10-35 kg) running on treadmills under controlled environmental conditions, or free-running, sometimes at extreme ambient temperatures. Principles and nutrient requirements obtained from these studies can probably be applied to intact trained dogs of other breeds but may be different for untrained, mostly inactive, neutered pet dogs that undertake intense activity only on weekends. Rather than seek dietary solutions to problems caused by a lack of training however, owners of these intermittently active dogs should exercise their dogs more frequently. Training, more than any change in diet, will improve performance and help to reduce the incidence of injury.

There are few studies of the effect of activity or ambient temperature on nutrient requirements in cats. Results obtained in dogs probably have limited relevance to cats because cats have a very specialized metabolism. Furthermore, cats are short-distance sprinters and jumpers, whereas dogs evolved for endurance. Also, there is less variation in the amount and quality of activity among cats, and the activity of pet cats is similar to that of laboratory cats. Outdoor cats and wild cats may be more active than laboratory cats but are able to supplement their food intake with prey. Nutrient requirements determined for laboratory cats are probably applicable, therefore, to pet cats undertaking a range of activities. Nutrient density may have to be increased, however, for cats undertaking very little activity to ensure that these animals receive sufficient essential nutrients while not becoming obese, and the energy density of the diet may have to be increased to support the activity of outdoor cats.

CALCULATIONS AND ASSUMPTIONS

Values are reported as means ± 2 standard deviations (SD) to encompass 95 percent of the population and more clearly represent the very wide individual variation in metabolic rate of dogs and cats. Where diet analyses have been provided in texts and nutrient digestibility has not been measured, metabolizable energy (ME) density has been calculated from the proximate analysis using the equations in Chapter 3. This ME density has then been used to calculate the nutrient density of protein, fat, and carbohydrate as grams per 1,000 kcal ME. These values are often slightly different than those generated by authors using Atwater or modified Atwater factors.

Many authors have expressed the requirements for each of the major nutrients (protein, fat, and carbohydrate) during exercise as percent ME. This was possible because modified Atwater factors made assumptions about the digestibility of each major nutrient. The equations in Chapter 3 estimate the energy digestibility of the entire diet, not the individual digestibilities of each major nutrient. It is not possible, therefore, to calculate the percent ME provided by each major nutrient precisely. Nevertheless, to help in comparisons with earlier recommendations, the percent ME from each major nutrient has been estimated by assuming that protein, fat, and carbohydrate all have the same digestibility. This probably slightly underestimates the digestibility and percent ME of fat and slightly overestimates the digestibility and percent ME of protein or carbohydrate, but the difference should be small.

Energy requirements relative to body weight or body weight raised to an exponent have not always been reported. These values have been calculated where possible using in-

dividual data; otherwise they have been calculated using either the means of body weight and energy consumption or the midpoint between the minimal and maximal body weight and energy consumption when only a range has been reported. The resulting values are, therefore, approximations of the true values relative to body weight and are indicated as such in the tables, but the error should be small except where body weights are not distributed normally.

Where studies have measured energy consumption indirectly by measuring oxygen (O_2) consumption, a standard assumption has been made that each liter of oxygen (L O_2) consumed represents 4.8 kcal (20.1 kJ) of heat production. The amount of energy generated for each liter of oxygen consumed would be lower when fat (4.7 kcal·L^{-1} O_2) and protein (4.6 kcal·L^{-1} O_2) were utilized and higher when carbohydrate was the fuel (5.1 kcal·L^{-1} O_2). A mixture of the major nutrients is used in most situations however, which is why 4.8 kcal·L^{-1} O_2 has been used when the respiratory quotient (RQ) has not been reported. The RQ is the ratio of the volume of oxygen metabolized by tissue to the volume of carbon dioxide generated by tissue. It provides some indication of the primary fuel being utilized during long-distance running because it approaches 1 when carbohydrate is the primary energy source but is 0.8 and 0.7, respectively, when protein and fat are the primary fuels. Young et al. (1959a) found that the RQ was closer to 1 in beagles during endurance exercise within 6 hours of a meal but was 0.8 during endurance exercise 24 hours after meal. Anderson and Lusk (1917) also reported that the RQ for a single dog was 0.8 during exercise after an 18-hour fast or immediately after a meat meal, but was close to 1 during exercise immediately after a glucose meal. Other studies in dogs have also reported a high RQ during exercise, but the timing of exercise relative to feeding was not reported (Cerretelli et al., 1964; Wagner et al., 1977). Using 4.8 kcal·L^{-1} O_2 will underestimate energy consumption in studies in which the RQ is high, but the error should be less than 4 percent.

HOW MUCH EXERCISE DO DOGS AND CATS UNDERTAKE?

Most studies of the activity of dogs and cats have been qualitative rather than quantitative. Nevertheless, qualitative reports suggest many similarities among cats and dogs whether caged or free. Most cats and dogs are inactive or asleep for large parts of each day. Long periods of inactivity are interspersed with short bouts of activity, but the activity pattern changes with time of day, ambient temperature, and human contact (Houpt, 1998).

Dogs

Beagles in cages slept or laid down for 60 percent of each day, sat for 11 percent, and stood for 26 percent (Hite et al., 1977). Hetts et al. (1992) found that beagles spent twice as much time sleeping when housed in pairs and moved about more when socially isolated, whereas Hubrecht et al. (1992) found that solitary dogs were inactive 80 percent of the time, and group-housed dogs were inactive only 60 percent of the time. Beagles in cages spent half as much time moving as those in pens or in cages with runs (Hetts et al., 1992). Tethered sled dogs spent 80 percent of each day recumbent, sat for 2 percent, stood for 10 percent, and moved about only for 5 percent of each day (Delude, 1986). Much of the activity was in response to human contact, but, in the absence of human intervention, activity peaked at sunrise and at sunset. Activity was unaffected by ambient temperature. O'Connor and Potts (1969) noted that some dogs in kennels were much more active and moved about continuously in the afternoons whereas others were much less active; both active and less active dogs were largely inactive at night from 1700 to 0800. Patil and Bisby (2002) reported that activity was higher among dogs in kennels than among dogs in the home environment, but more dogs in kennels were small. Small-breed dogs (Manchester terriers) were active for twice as many hours as large dogs (Labradors). Activity and ME intake were similar in kennels as in the home environment among middle- and large-breed dogs. In Britain, Downs et al. (1997b) and Butterwick and Hawthorne (1998) observed that both working and pet Border collies spent half their time running and one-quarter of their time walking during an exercise period and appeared to utilize similar amounts of energy when allowance was made for duration of exercise. More working dogs worked longer each day, and some older pet dogs spent all of each exercise period walking and not running. Head et al. (1997) and Siwak et al. (2002) noted a decrease in spontaneous activity with age in healthy beagles in their home cage and in healthy pound dogs in a test room but not in beagles in the test room. Breed and environment, therefore, determine whether spontaneous activity declines with age. Dogs also tended to roam less after they have been neutered (Hopkins et al., 1976).

Free-living suburban dogs were also observed resting approximately half of the time (Berman and Dunbar, 1983). The amount of activity was greatly affected by changes in ambient temperature (from 9 to 29°C), with sightings of free-ranging dogs increasing to a maximum at 23°C and then declining as ambient temperature increased. In the winter months, sightings of urban and suburban dogs were greatest just after noon but in the summer were highest at sunrise and in the late afternoon with some activity continuing at night (Beck, 1973; Berman and Dunbar, 1983; Lehner et al., 1983). Dill et al. (1933) also noted greatly reduced exercise capacity in a dog when the ambient temperature was 40°C in the shade compared to when it was 20°C. Some of the increase in energy requirements of dogs in winter months, therefore, may be associated with increased exercise in the cold as well as cold-induced thermogenesis.

In summary, most dogs, although not all pet dogs, are minimally active. There is considerable variation in activity

among individuals, among sizes of dogs, with degree of confinement, with age, with ambient temperature, and with the extent of human and canine contact. Therefore, it is not possible to generalize about a particular situation. When considering how much activity an animal undertakes and how much food it requires, each dog must be treated as an individual: It is less important to classify a dog as working or pet, caged or kenneled than to classify the dog by its activity level, particularly the duration of any exercise period and the distance traveled.

Cats

Laboratory cats and free-ranging farm cats, like dogs, are active in short 2-hour bursts but spend much of their day asleep (Houpt, 1998). Panaman (1981) observed that farm cats spent 62 percent of the day sleeping or resting, 15 percent hunting, and 2 percent traveling. Cats spent 80 percent of their time in a home area of between 0.7 and 15 hectares (ha) and traveled 1.8 ± 1.5 km daily only when hunting. Cats were active mainly during the day, hunting primarily at noon and at dusk, and mostly slept at night. Berman and Dunbar (1983), however, found that free-ranging suburban cats were sighted more at night, with sightings constant up to 17°C and then decreasing as the temperature increased further. Laboratory cats sleep for slightly more time each day, probably because there is less concern about the food supply. Food-deprived cats tend to sleep less, and cats fed more times daily or older cats more than 10 years of age tend to sleep more (Houpt, 1998). Like dogs, most cats, but not all pet cats, are minimally active. It is more important to consider the activity level of a cat than to classify it according to its degree of confinement. Nevertheless, the variation in activity is much less than in dogs because the distance traveled is quite short even for a free-ranging cat.

TYPES OF EXERCISE: SPRINTING VERSUS ENDURANCE

Sprint Exercise Over a Distance of Less Than One Kilometer

Greyhounds commonly sprint over distances less than 1 km around oval tracks approximately 400 m in circumference. Common names, distances, approximate best times, and average speeds of greyhound races in the United States are listed in Table 11-1. Ambient temperatures are rarely below freezing and are often very high. Anaerobic as well as aerobic sources of energy are important in this sprint type of racing.

TABLE 11-1 Greyhound Race Distances and Approximate Fastest Times at Tracks in the United States

Common Name	Distance (miles)	Approximate Distance (m)	Approximate Best Times (s)	Average Speed ($km \cdot h^{-1}$)
Short Sprint	3/16	300	17	64
Sprint	5/16	500	30	60
Middle Distance	3/8	600	37	59
Marathon	7/16	700	43	59
Super Marathon	9/16	900	57	57

SOURCE: American Greyhound Track Operators Association, 2001.

Endurance Exercise Over Distances Greater Than One Kilometer

Trained sled dogs can maintain an Iditarod-type trot of approximately 16 $km \cdot h^{-1}$ for 10-14 hours per day (Grandjean and Paragon, 1992). Sled dogs compete in "sprint" races (Table 11-2) in which they pull lightweight sleds over distances of less than 30 km, "middle-distance" races of approximately 50 km, or "long-distance" races of 1,000 km or more over many days, often pulling heavy loads. Ambient temperatures are often low and sometimes well below freezing. Aerobic metabolism provides most of the energy for this endurance-type exercise.

The type of exercise performed by pet and working dogs varies with the nature of the activity that they are required by their owner to undertake. Chasing flying discs or sticks involves sprinting, whereas running in company with a jogger involves endurance exercise. Retrieving gun dogs and security dogs are required to undertake many short sprints of much less than a kilometer. Hunting or tracking dogs and search-and-rescue dogs undertake exercise that is more endurance in nature but does not involve the resistive component required of sled dogs.

TRADITIONAL DIETS FED TO RACING DOGS

Sled Dogs

Sled dogs were fed "pemmican and fresh meat" during Amundsen's successful 740-km round trip to the South Pole in 1911 (Editor's note, Hanssen, 1937). Dogs maintained body condition and gained weight despite hauling sleds with initial weights of 450-500 kg for an average of 41 $km \cdot d^{-1}$ and one ascent of 3,400 m. Hadwen (1937), however, noted that many explorers in both the Arctic and the Antarctic reached their goals at the expense of their dogs, which were sacrificed to feed the living, though "the latter are not in much better condition than those which were killed." Lack of a balanced food was offered as a cause for "nervous diseases and malnutrition."

In the Antarctic in the middle of the twentieth century, dogs at the base camp were fed on alternate days 2.5-3.5 kg of seal meat, most of which was muscle, fat, and bone with liver and heart added occasionally (Taylor et al. 1958). A concentrated dry ration (Sled Dog Diet A), provided on journeys, consisted by weight of 70 percent beef meal, 22 percent beef fat, 4 percent yeast extract, and 4 percent bone

TABLE 11-2 Distances and Reported Times for Some Long-Distance Races

Race	Location	Ambient Temperature (°C)	Distance (km)	Duration (h)	Average[a] Speed ($km \cdot h^{-1}$)	Reference
Copper Basin 300	Alaska	–10 to –35	490	70	7	Hinchcliff et al., 1997a Hinchcliff et al., 1997b
Iditarod Trail Race	Alaska		1,790	Median 254 Winner 222	7 8	Piercy et al., 2001b
Yukon Quest International	Yukon Territories and Alaska	–7 to –30				Hinchcliff et al., 1993
Dawson City (race midpoint) to Eagle			256	34	7.5	
Eagle to Fairbanks			664	95	7	

[a]These values do not take account of rest stops. Dogs will have run faster than this average between rest stops.

meal, which was fed in 0.45-kg blocks. Mixed with some fresh meat, the diet was fed on journeys of more than 1,000 miles but caused diarrhea, and dogs lost weight during heavy work. Taylor et al. (1958) developed a new diet containing less protein but more fat and vitamins (Sled Dog Diet B), consisting of 25 percent white fish meal, 15 percent skim milk powder, 10 percent precooked cornstarch, 20 percent margarine, 25 percent beef suet, 5 percent yeast extract, and 4 percent bone meal by weight, also fed in 0.45-kg blocks. After 1958, a modified diet (Sled Dog Diet C) substituted whale meat for fish meal (Orr, 1966). Both Wyatt (1963) and Orr (1966) showed that 0.45 kg of any of these diets provided insufficient energy for sled dogs working at very cold temperatures and suggested that the amount fed should be doubled for working dogs. The analyses of these diets are tabulated in Table 11-3.

In the Arctic, natives fed dogs walrus, seal, whale, bear, beaver, caribou, or reindeer meat (Coppinger, 1977). Blubber was added ("to aid digestion") when fish was fed (Croft, 1937). Before snowmobiles, the 400 sled dogs on Southampton Island in Hudson Bay consumed 50,000 kg of meat and 16,000 kg of fat annually (Coppinger, 1977). This is equivalent to each dog consuming approximately 1,600 kcal $ME \cdot d^{-1}$ of a diet containing approximately 20 percent ME as protein and 80 percent ME as fat. In Alaska, 30-45-kg body weight (BW) sled dogs were fed mostly sun-dried salmon: 0.45 kg when idle and 0.9 kg during work (equivalent to 2.7 kg of fresh fish), which provided approximately 4,000 kcal ME, 62 percent ME as protein and 38 percent ME as fat (Hadwen, 1937). In West Greenland, 30-35-kg BW dogs were fed as much as 2.7 $kg \cdot d^{-1}$ of fresh food (mostly walrus) during cold weather (Croft, 1937). On journeys, dogs were

TABLE 11-3 Analyses of Diets Fed to Working Sled Dogs in the Antarctic, Mid-Twentieth Century

Nutrient Content	Sled Dog Diet A[a]	Sled Dog Diet B[b]	Sled Dog Diet C[c]	Seal Meat with Blubber[c]	Lean Seal Meat[c]
ME ($kcal \cdot g^{-1}$ as fed)	4.6-4.8	5.3	4.8	4.3	1.2
Moisture (% as fed)	4-9	8-9	5	45	72
Protein ($g \cdot 1{,}000\ kcal^{-1}$)	129-140	56	43	42	216
% ME	44-48	23-24	15	18	99
Fat ($g \cdot 1{,}000\ kcal^{-1}$)	58-62	72-79	84	90	3
% ME	52-55	64-69	67	82	1
Carbohydrate ($g \cdot 1{,}000\ kcal^{-1}$)	0-4	21-34	48	0	0
% ME	0-2	8-13	18		
Calcium ($g \cdot 1{,}000\ kcal^{-1}$)	0.2-1.6	2.1-3.0	4.3	0.02	0.03
Phosphorus ($g \cdot 1{,}000\ kcal^{-1}$)	0.5-1.1	1.6-2.0	2.1	0.2	1.8
Magnesium ($g \cdot 1{,}000\ kcal^{-1}$)	0.04-0.07	0.14-0.16	0.13	0.03	0.21
Sodium ($g \cdot 1{,}000\ kcal^{-1}$)	0.7	0.9	0.9	0.2	0.4
Potassium ($g \cdot 1{,}000\ kcal^{-1}$)	0.3	1.1-1.2	1.0	0.04	3.8
Chloride ($g \cdot 1{,}000\ kcal^{-1}$)	0.9	1.1	1.2	0.2	0.4
Iron ($g \cdot 1{,}000\ kcal^{-1}$)	0.05-0.07	0.01	—	0.02	—
Protein digestibility (%)	61-79	89-90	75	92	98
Fat digestibility (%)	93-97	94-97	87	99	41

[a]Taylor et al. (1958); Wyatt (1963); Orr (1966).
[b]Wyatt (1963).
[c]Orr (1966).

fed 0.45 kg·d^{-1} of dog pemmican ("a concentrated form of fresh beef containing 28 percent fat and 65 percent protein"). Dogs were fed dried sealmeat, raw fish, beaver meat, tallow, and high-protein dog foods during the first Iditarod Trail Race (Adkins and Morris, 1975). Kronfeld (1973) reported that trainers in North America fed meat and cereal with corn oil added according to work performance needs.

In Europe, Ebing and Beynen (1999) found that the training ration fed by five Dutch mushers to their dogs for sprint, middle- and long-distance racing was nutritionally complete and contained 59-80 g per 1,000 kcal ME (24-34 percent ME) as crude protein, 28-53 g per 1,000 kcal ME (25-46 percent ME) as crude fat, and 72-128 g per 1,000 kcal ME (28-49 percent ME) as carbohydrate. These mushers fed a commercial dry ration mixed with chicken, rumen, sunflower oil, cocoa fat, buttermilk, vitamins, and/or yeast.

Decombaz (1995) reported that food given by an "experienced musher" from Alaska during the Alpirod contained 72 percent gross energy as fat and 28 percent gross energy as protein. Most (76 percent) gross energy came from a single evening meal; the remainder was supplied as a snack of white fish, lamb, or sausage.

Greyhounds

Most greyhound trainers in the United States feed thawed raw meat mixed with a commercial dry dog food together with various other ingredients including vitamins, minerals, vegetables, buttermilk, and cider vinegar. This raw meat contains varying amounts of protein and fat: one sample contained 117 g per 1,000 kcal ME (49 percent ME) as crude protein and 56 g per 1,000 kcal ME (47 percent ME) as ether extract; another sample contained 180 g per 1,000 kcal ME (73 percent ME) as crude protein and 29 g per 1,000 kcal ME (24 percent ME) as ether extract. Both contained very little (<11 g per 1,000 kcal or <4 percent ME) carbohydrate. This carbohydrate, measured as nitrogen-free extract (NFE), was mostly charcoal. The composition of a dry diet-meat mixture depends on the relative proportions and composition of the meat and dry diet but adding meat to a dry diet, usually increases the fat and protein content of the diet.

DIET AND HEALTH DURING EXERCISE

Diet may ameliorate some racing-related conditions. Rapid changes in diet at the onset of a race can cause diarrhea, which can be exacerbated by stress and dehydration during the race, whereas feeding dried fish containing bones has been associated with constipation (Adkins and Morris, 1975). Increasing the digestibility of protein in the diet prevented diarrhea in sled dogs working in the Antarctic (Taylor et al., 1958). Providing adequate water may prevent dehydration and can reduce exercise-induced hyperthermia (Young et al., 1959a; Baker et al., 1983). Supplementary antioxidants may reduce oxidative injury during exercise (Baskin et al., 2000). Dogs with high serum concentrations of vitamin E in the blood before the Iditarod were almost twice as likely to finish the race (Piercy et al., 2001a). Strategies to increase stamina by maintaining glycogen stores in muscles also may help to reduce athletic injuries in dogs; Yoshikawa et al. (1994) found a 26-35 percent increase in peak bone strain in the tibia of foxhounds when muscles showed myoelectrical changes suggestive of muscle fatigue. Human skiers are reported to have more injuries toward the end of the day, and skiers themselves report being too tired to avoid a fall presumably because fast-twitch fibers that would be used to avoid difficult situations are depleted of glycogen (Brouns et al., 1986).

Effect of Exercise on Intestinal Function

Changes in intestinal function have also been observed in dogs after short periods of activity at levels of exercise less than 80 percent of maximal (Tasler et al., 1974; Kenney et al., 1988; Kondo et al., 1994). In untrained 18- to 25-kg mongrel dogs running on a treadmill with an 8 percent slope at 6 km·h^{-1} (when heart rate was only 60-70 percent of maximum), acid secretion was unaffected during the first hour of exercise after a 380-kcal ME canned meal but decreased to 30 percent of resting values during the second hour of exercise (Kondo et al., 1994). Intestinal motility was also disrupted, and gastric emptying of a 390-kcal ME liquid meal was delayed (the half-time was increased 25 percent) during exercise in these dogs (Kondo et al., 1994). In food-deprived dogs, the pattern of myoelectrical activity characteristic of the unfed state, the migrating motor complex (MMC), was abolished until after exercise had stopped, whereas after a meal, the fed pattern of myoelectric activity in the duodenum was interrupted during exercise by strong contractions (Kondo et al., 1994). This disruption of duodenal activity after a meal, including conversion of the fed pattern to an MMC pattern, was also seen in untrained dogs running at only 50-70 percent of maximal heart rate for 30-90 minutes (Kenney et al., 1988).

Gastric acid secretion and the volume and bicarbonate content of pancreatic juice secreted in response to food also decreased 40-50 percent in trained 16- to 20-kg mongrel dogs running at 10 km·h^{-1} on an 8 percent slope (probably relatively close to maximal) for just 15 minutes (Tasler et al., 1974). Mucosal blood flow was decreased by 15 percent during this exercise and for a short period afterwards. In anesthetized greyhounds, a decrease in blood flow of 50 percent to the intestine was associated with a marked decrease in intestinal wall pH, suggesting that some degree of ischemia and infusion of cream into the stomach caused a local hyperemia that exacerbated jejunal ischemia (Poole et al., 1987). Feeding dogs a meal immediately before or during a bout of intense exercise would seem, therefore, to be unwise, but how long exercise should be deferred after a meal is unknown.

Sled Dog Diet A (0.45 kg) fed to dogs in fairly large pieces was found to clear from the stomach of working sled dogs in the Antarctic between 14 and 18 hours after a meal (Taylor et al., 1958). In sedentary dogs, De Wever et al. (1978) reported that the fed pattern of myoelectric activity in the intestine disrupted the MMC for 5.5 ± 4 hours after a commercial low-fat dog food meal providing approximately one-third of the daily maintenance energy requirement (MER). The duration of this fed pattern increased proportionately with the size of meal to 13 ± 6.5 hours when the entire daily MER was fed as a single meal. Medium-chain triglycerides (10 kcal ME·kg BW^{-1}) disrupted the pattern for longer (10.5 ± 8 hours) than 30 kcal ME·kg BW^{-1} of long-chain peanut oil (6 ± 2 hours), sucrose (3 ± 1 hours), or milk proteins (1.5 ± 1 hours), but duration of disruption depended more on the physicochemical properties of the food than on its volume or caloric content (De Wever et al., 1978).

Racing sled dogs consume much larger meals than sedentary dogs, but no studies to date have reported the rate of gastric emptying, the duration of disruption of the MMC by a fed pattern, or the duration of small intestinal transit in these dogs after a meal. To allow for intestinal transit, individual dogs may need more or less time depending on the composition of the diet and the level and type of activity, but intense exercise should probably be delayed 4-8 hours after a meal that provides one-third of the daily MER, and should be delayed 10-16 hours after a meal providing the entire daily MER.

Exercise and Digestibility

The effect of exercise on digestibility of nutrients in dogs has not been determined. The digestibility of diets fed to sled dogs or beagles has been measured mostly in sedentary dogs (Taylor et al., 1958; Downey et al., 1980). In greyhounds being raced twice weekly, the average digestibility of four mixed protein dry diets was comparatively high (>80 percent for protein and dry matter, >90 percent for fat and NFE), but digestibility was measured on days when dogs were not being raced (Hill et al., 2000, 2001b). In military dogs in training fed six dry diets and four experimental diets with soy or fish meal as the primary sources of protein, dry matter (DM) digestibility and crude protein digestibility were 71-75 percent and 68-79 percent, respectively (Wolter et al., 1980). Orr (1966) reported that protein digestibility was very high (98 percent) in sled dogs fed lean seal meat, but Taylor et al. (1958) and Orr (1966) reported that the digestibility of protein in Sled Dog Diet A (made with beef meal and beef fat) and in Sled Dog Diet C (made with dehydrated whale meat) was very low (61-70 percent and 75 percent, respectively). Wyatt (1963) reported that protein digestibilities of Sled Dog Diet A (made with beef) and Sled Dog Diet B (made with fish meal and skimmed milk) were higher (79 percent and 90 percent, respectively) in tethered sled dogs, and higher still (89 percent and 93 percent, respectively) in working dogs. Wyatt (1963) and Orr (1966) suggested that processing such as heat treatment (steam washing of minced beef) might have been responsible for the poor digestibility of protein in these diets. The digestibility of fat was uniformly reported to be high (87-97 percent) in both working and tethered dogs in all of these studies, except that the digestibility of fat in lean seal meat was very low (41 percent). Endogenous fat would have lowered the apparent digestibility of fat in seal meat, however, because seal meat contained almost no fat and endogenous fat would have been a greater proportion of fecal fat.

Taylor et al. (1958), Wyatt (1963), and Orr (1966) reported that when working sled dogs were fed Sled Dog Diet A, their feces became dark and liquid, indican appeared in the urine, dogs became coprophagic and lost weight, and one dog became listless and apathetic and started to vomit. Dogs and their feces became normal and dogs performed better either when fed a diet containing less protein and more carbohydrate, such as Sled Dog Diet B, or when fed a more digestible source of protein such as seal meat. Much more nitrogen was excreted in the feces of dogs fed Sled Dog Diet A (14-22 $g \cdot d^{-1}$) than in those fed Sled Dog Diet C and seal meat (4 and 1 $g \cdot d^{-1}$, respectively) because Sled Dog Diet A contained more protein, and the protein was less digestible. This suggests that the diarrhea and other changes in dogs fed Sled Dog Diet A were associated with indigestible protein and that dogs fed high-protein foods should be fed very digestible sources of protein. Sudden increases in food intake can also cause diarrhea. Food intake and exercise should be increased gradually therefore at the onset of training.

When to Feed Exercising Dogs

A variety of feeding times relative to exercise has been reported in dogs, although there is little evidence to support or disagree with any of these practices. Reports have described mushers feeding their sled dogs snacks during the longer stages of a race and a main meal at the end of each stage (Decombaz, 1995), giving snacks during rest stops between two 4-6 hour periods of running, followed by a full meal at the end of each day (Reynolds et al., 1997), or providing water and food at rest stops every 2-4 hours (Hinchcliff et al., 1997b) during long races. Kohnke (1997) has advocated feeding a small meal (weighing <1 percent of body weight) to greyhounds prior to a race to provide a ready source of energy but recommends feeding at least 6-8 hours before exercise to allow time for digestion. Broun (1923a), however, reported that dogs vomited when given food before or during but not after intense endurance exercise.

Hypoglycemia and ketosis contribute to loss of endurance when human athletes fast, but this does not appear to be true for food-deprived dogs. Young (1959) found blood lactate and acetone concentrations were unaffected either by exercise to exhaustion or by 5 days of food deprivation that resulted in a 10 percent loss of body weight in trained young

adult beagles running at approximately 50 percent of peak effort (6 km·h^{-1} on a 17 percent slope). The mean blood glucose concentration was 20 percent lower (69 vs. 86 mg·dL^{-1}) before exercise in food-deprived dogs but did not decline with exhaustive exercise, whereas blood glucose decreased 45 percent during exercise in dogs that were not deprived of food, with the result that postexercise blood glucose was higher in food-deprived dogs. Endurance and average energy expenditure were unaffected by food deprivation when no water was provided during exercise, but endurance increased 74 percent after food deprivation when water was provided during exercise; one dog ran 140 miles over 39 hours without stopping after being deprived of food for 5 days.

Young et al. (1959a, 1962) found no effect of time of feeding (from 1.5 to 24 hours prior to exercise) on mean energy expenditure during 40 minutes of exercise when a low-fat (19 percent ME), high-carbohydrate (53 percent ME) meal providing most of their daily energy requirement was fed to these dogs. Nevertheless, carbohydrate provided more energy for exercise (70 percent vs. 45 percent), fat provided less energy (24 percent vs. 53 percent), and RQ was higher (0.93 vs. 0.79) during exercise performed within 6 hours postprandially than for exercise performed 17 or more hours postprandially. Young et al. (1959a) also found that administration of 5 g·kg BW^{-1} of carbohydrate (composed of a mixture of starch, dextrins, glucose, and sucrose) 30 minutes before exercise had no effect on endurance capacity of these dogs, but increased RQ from 0.77 to 0.85 and reduced the average decline in blood glucose concentration during exercise from 39 to 20 mg·dL^{-1}. When offered free choice during exercise, water and solutions containing 50 g·L^{-1} glucose or 35 g·L^{-1} lactalbumin did not affect endurance, but whole milk, a 3.5 g·L^{-1} plant phospholipid solution, and a vitamin solution (containing 3 mg·L^{-1} niacin, 3 mg·L^{-1} pantothenic acid, 0.7 mg·L^{-1} riboflavin, 0.4 mg·L^{-1} thiamin, and 0.4 mg·L^{-1} pyroxidine) all reduced endurance, and a mineral solution (containing 1.6 g K·L^{-1}, 0.9 g P·L^{-1}, 0.5 g Na·L^{-1}, and 0.2 g·L^{-1} Mg, Cu, and Fe) caused diarrhea (Young et al., 1960). Mean RQ was 1.03 in dogs receiving milk, protein, and glucose but 0.83 in dogs receiving water, vitamins, or phospholipids. Kruk et al. (1987) reported when 15- to 24-kg mongrel dogs were infused with 3-4 g·kg BW^{-1} of glucose while running for 2 hours on a treadmill at 4-5 km·h^{-1}, RQ was increased, oxygen consumption was reduced by 16 percent, and the mean increase in rectal and muscle temperatures decreased by 0.9°C because the amount of heat dissipated by the body was 2 percent higher compared to saline-infused controls. Dogs given 100-150 mL of soybean oil 4 hours before exercise and intravenous heparin to increase free fatty acid (FFA) concentrations in the blood consumed more oxygen, and there was a trend to less efficient thermoregulation.

Budohoski et al. (1982) found that skeletal muscle lipoprotein lipase activity increased during exercise in food-deprived dogs but was low and remained low during exercise in dogs 4 hours after a high-fat meal. Falecka-Wieczorek and Kaciuba-Uscilko (1984) found evidence of increased fat utilization during moderately intense exercise in dogs exercised 4 hours after a high-fat (71 percent ME), low-carbohydrate (23 percent ME) meal (220 kcal ME·kg BW$^{-0.75}$) compared to dogs exercised 4 hours after a low-fat (13 percent ME), high-carbohydrate (70 percent ME) meal or dogs exercised after 20 hours of food deprivation. Plasma triglyceride concentrations remained high in unexercised control dogs fed the high-fat diet, were low and increased during exercise in food-deprived dogs and dogs exercised after the low-fat meal, but were high and decreased during exercise in dogs fed the high-fat meal. Thus, chylomicron uptake by muscle appeared to increase during exercise after a high-fat meal, but there was either reduced uptake or increased production of triglyceride during exercise after a low-fat meal and after food deprivation. Plasma free fatty acids (FFA) concentrations were higher in dogs fed the high-fat meal but increased during exercise whether dogs were fasted, fed a high-fat meal, or fed a low-fat meal. The utilization of FFAs also appeared to be greater in dogs fed the high-fat meal however, because plasma glycerol increased more rapidly and the ratio of FFAs to glycerol fell more rapidly during exercise in dogs fed the high-fat meal than in fasted dogs or dogs fed the low-fat meal. Increased fat utilization in dogs fed the high-fat diet could reduce glycogen utilization, but blood glucose concentrations declined similarly in all three groups and glucose concentrations were higher in dogs fed the high-carbohydrate, low-fat meal.

Reynolds et al. (1997) found that orally giving Alaskan huskies 500 mL of a solution containing 1.5 mg·kg BW^{-1} of glucose polymer immediately after pulling an all-terrain vehicle and driver 30 km as a 12-dog team, promoted recovery between bouts of exercise by returning plasma glucose and muscle glycogen concentrations to pre-race concentrations more rapidly. Wakshlag et al. (2002b), however, showed that addition of 0.5 g·kg BW^{-1} of protein to 1.5 g·kg BW^{-1} of the same glucose polymer given orally immediately after exercise had no additional benefit on the rate of increase in glycogen concentrations in skeletal muscle after 30 minutes at 23 km·h^{-1} on a treadmill (1 percent slope). Galassetti et al. (1999a) showed that uptake of glucose by liver and muscle is enhanced in mongrel dogs immediately after 150 minutes of exercise at 50 percent of maximal heart rate. Glucose in the portal vein usually provides a "portal signal," which stimulates hepatic glucose uptake but inhibits skeletal muscle glucose uptake in sedentary animals. Galassetti et al. (1999b) showed that infusion of glucose into the portal vein of mongrel dogs after this moderate-intensity exercise stimulated hepatic glucose uptake and also increased skeletal muscle glucose uptake by eliminating the inhibitory effect of the portal signal on skeletal muscle uptake. Hamilton et al. (1996) showed that, when glucose was infused into the

duodenum of mongrel dogs (1.2 g·kg BW^{-1} over 150 minutes), glycogen deposition in muscle increased threefold 30 to 180 minutes after exercise (150 minutes at 50 percent of maximal oxygen consumption) compared to rested controls and that the increase in glucose uptake by muscle was facilitated by more rapid glucose uptake by the intestinal mucosa.

Proteins in skeletal muscle and in the gut are catabolized during exercise. Williams et al. (1996) have pointed out that amino acids depleted in the gut during prolonged endurance exercise are replenished from the lumen when dogs are fed immediately after exercise. Okamura et al. (1997) noted greater benefit when a 10 percent glucose solution mixed with a 10 percent amino acid solution was infused intravenously into beagles immediately after 150 minutes of moderately intense exercise (60 percent of maximum), compared to when the solution was infused 2 hours after exercise. The rates of protein synthesis and breakdown in skeletal muscle did not increase above resting levels in these dogs during recovery unless supplemental nutrients were provided. Protein synthesis doubled and protein breakdown halved in skeletal muscle when amino acids were infused immediately after exercise. Amino acid and glucose plasma concentrations and uptake by skeletal muscle also increased when nutrients were infused. Provision of amino acids was essential therefore to allow protein accretion after exercise, but the benefits of early versus late infusion were less clear. Uptakes across the hind-limb of some amino acids were higher and some lower during early compared to late infusion, but uptake of glucose was higher in dogs infused early. Phenylalanine uptake was twice as high and protein synthesis 30 percent higher during early infusion than during later infusion.

In summary, dogs should be fed immediately after intense exercise. Currently, it appears that dogs should not be fed meals containing fat immediately before or during intense exercise. To allow for gastric emptying, ideally dogs should not undertake intense exercise within 8 hours of a small meal or 16 hours of a large meal, although this is obviously impractical with some racing dogs. During exercise, it is more important to provide free-choice water than other nutrients. Glucose (up to 5 g·kg BW^{-1}) given before, during, or after exercise has been shown to minimize the decline in blood glucose observed during exercise, promote more rapid repletion of muscle glycogen after exercise, and improve thermoregulation.

EXERCISE AND BODY CONDITION

In human athletes, gradual weight reduction by calorie restriction does not appear to greatly affect performance, maximal oxygen consumption ($\dot{V}O_2max$), strength, or endurance, provided enough carbohydrate, protein, and other essential nutrients are included in the diet to maintain glycogen stores and muscle mass (McMurray et al., 1985; Horswill et al., 1990; Fogelholm, 1994). Greyhound trainers, however, restrict the amount of food fed to their racing dogs because dogs are purported to run faster when food is restricted slightly. One abstract lends support to this notion (Hill et al., 1999b). The abstract reports that racing greyhounds ran 0.2 $m \cdot s^{-1}$ faster over a 500-m sprint race when food intake was restricted to 85 percent of free-choice and body weight was 6 percent less than when dogs were fed free-choice. This change in performance is equivalent to 6 m over a 500-m race and would often be the difference between winning and losing a race. Mean segmented neutrophil numbers were slightly fewer (2,200 vs. 2,800·μL^{-1}) in food-restricted dogs.

Few studies have examined the effect of body condition on endurance exercise. Body weight and body conformation were not associated with whether dogs finished the Iditarod (Constable et al., 1996). Hinchcliff et al. (1998), however, reported that dogs that did not finish the Iditarod lost more weight (9 percent vs. 5 percent) than dogs that finished the race. The highest $\dot{V}O_2max$ ever reported in dogs was measured by Reynolds et al. (1999) in sled dogs with a lean body condition. Young (1959) reported that weight loss associated with 5 days of food deprivation increased endurance in young adult beagles running at 6 $km \cdot h^{-1}$ on a treadmill with the incline varied to maintain a constant work load (approximately 50 percent $\dot{V}O_2max$). Nevertheless, this increase in endurance was probably a result of metabolic changes associated with food deprivation because there was no change in energy expenditure when corrected for changes in body weight. Young (1960) also examined the effect of gradual weight gain on energy consumption during exercise in these beagles. Dogs gained lean body mass, fat mass, and body water over several months, but body fat increased only from 17 to 20 percent of the total. As mean body weight increased from 10.4 to 12.4 kg, mean energy expenditure at rest (56 kcal·kg $BW^{-1} \cdot d^{-1}$) and during 50 minutes' exercise (3.6 $kcal \cdot min^{-1}$) (Reynolds et al., 1999) did not change, but mean RQ during exercise increased from 0.81 to 0.95, suggesting a greater reliance on carbohydrate, and average water loss increased from 1.2 to 1.8 $mL \cdot kcal^{-1}$.

Orthopedic problems also appear to be more common in obese dogs and cats. "Locomotor problems" were more common in grossly obese dogs in the United Kingdom (Edney and Smith, 1986), and lameness was more common in heavy cats in the United States (Scarlett and Donoghue, 1998). The prevalence of hip dysplasia and the prevalence and severity of osteoarthritis were much lower in retrievers that received 25 percent less food than in control dogs given free access to food (Kealy et al., 1992, 2000). The body condition score on a 9-point scale was 6.7 ± 0.4 in those dogs given free access to food and 4.6 ± 0.4 in restricted-fed dogs (Kealy et al., 2002). It is worth noting (for dogs fed raw meat) that obesity was also associated with an increased risk of infection from *Salmonella* (Williams and Newberne, 1971).

It appears wise, therefore, to keep exercising dogs lean. An ideal body condition score for most breeds would be 4-5 on a scale of 1 to 9 such as that developed by Laflamme (1997). Greyhounds have less body fat, however, than other breeds (Gunn, 1978b), and an ideal body condition score for racing greyhounds and other sight-hounds is slightly less (approximately 3.5 on a 9-point scale). Reynolds et al. (1999) described the ideal body condition in sled dogs as "easily palpable ribs and spinous processes and a slight depression between the wings of the ileum," corresponding to a score of 2.5 on a 1 to 5 scale (4 on a 9-point scale).

EFFECT OF CONFINEMENT AND TRAINING

Confinement in a cage or a regime of regular exercise results in adaptations that may affect nutrient requirements. Most studies of the effect of exercise on nutrient requirements have been performed on trained dogs exercising regularly, but requirements determined for trained dogs may not be the same as requirements for untrained pet dogs exercising only intermittently on weekends. A few studies, however, have examined the effect of confinement and training on dogs. There appear to be no studies of cats.

Most training of dogs involves "continuous" training for endurance exercise in which dogs run aerobically at 50-80 percent of either maximal heart rate or maximal oxygen consumption for 30 to 90 minutes daily for 6-8 weeks. Reynolds et al. (1999) and Ready and Morgan (1984) assessed the effect of "interval" training on dogs by running sled dogs on a treadmill supramaximally two to three times weekly as well as exercising dogs submaximally two to three times weekly. Greyhounds training for sprint exercise have also been raced or run supramaximally twice weekly and exercised submaximally every day either by walking several miles daily or by being released in a 900-m^2 pen twice daily (Staaden, 1984; Hill et al., 2000, 2001b). All studies have increased exercise gradually. None has examined the effect of sudden increases in activity.

Morpurgo (1897) and Siebert (1928) both reported that training increased muscle mass in dogs by hypertrophy of individual muscle fibers, not by hyperplasia. Friedländer and Thierse (1928) reported that the bones of a leg inactivated with a stiff bandage became lighter, more slender, and longer, with a more actively growing epiphyseal line, and contained less water and mineral. Steinhaus et al. (1932), however, did not find any hypertrophy of skeletal muscle or of limb bones in dogs exercised by running or swimming. Kohlsrauch (1929) suggested that canine muscle hypertrophied only if the speed of exercise was increased. This may explain why trained greyhounds are subjectively more muscular than untrained greyhounds, whereas dogs undertaking endurance exercise do not necessarily show increased muscle bulk. Tipton et al. (1970) found that the strength, diameter, and collagen content of lateral collateral ligaments was highest in trained dogs compared to untrained dogs, and lowest from immobilized limbs. Laros et al. (1971) found that the insertions of the lateral collateral ligaments but not other ligaments in the knee were strongest in dogs kept in pens compared to dogs kept in cages but weakest in immobilized limbs. As little as 6 weeks of caging resulted in subperiosteal bone resorption at the insertion of the ligament, but over 6 months, fibrous tissue replaced resorbed bone and became mineralized. Inactivity, therefore, was associated with bone resorption followed by bone accretion. Külbs (1912, 1929), Grober (1908), Thörner (1930), Steinhaus et al. (1932), Bove et al. (1979), and Arokoski et al. (1993) all found that the heart was larger relative to body weight in trained dogs, and Steinhaus (1932) showed that heart size declined again when dogs became inactive. More recently, using echocardiography, Stepien et al. (1998) reported a 24 percent increase in heart mass index in both "veteran" and "rookie" sled dogs during a 5-month winter season in which dogs ran approximately 20 km daily at 30-40 percent $\dot{V}O_2max$. Changes in other organs with exercise have been inconsistent and have been performed only on small groups of dogs. Thus, Külbs (1912) and Thörner (1930) found that the lungs and kidneys were heavier in exercised dogs than in unexercised litter mates, but Steinhaus et al. (1932) found no effect of running exercise on lung or kidney weight and heavier kidneys and lighter lungs in dogs exercised by swimming. Külbs (1912) reported an increase in liver weight in trained dogs, but Thörner (1930) and Steinhaus et al. (1932) found no difference from unexercised controls.

Examining the effect of daily long-distance aerobic exercise (5-7 $km \cdot h^{-1}$ on 15 percent slope) on growing beagles, Arokoski et al. (1993) found food intake did not increase greatly after 6 months of age in caged dogs, but increased almost linearly in running dogs as distance increased to 40 $km \cdot d^{-1}$ by 1 year of age. At 1 year of age, body mass was higher in running dogs, but by 70 weeks of age, body mass and muscle mass did not differ from those of caged control dogs; the bone mass relative to body mass of radius and tibia was approximately 10 percent greater, however, in running dogs. Puustjärvi et al. (1991, 1992, 1995) reported that, although more osteophytes developed and weight-bearing bones grew larger in running dogs, bone mineral density was lower in the vertebrae, ileum, and radius of running beagles compared to caged controls. Some markers of bone metabolism were increased (median serum alkaline phosphatase concentrations doubled) and median serum estradiol concentrations were 25 percent lower in running dogs, but osteoblast markers of bone metabolism (concentrations of serum osteocalcin and carboxyl terminal [C-terminal] propeptide of type I collagen) were unchanged by regular exercise. Median daily urinary calcium excretion doubled from 0.3 mmol in sedentary dogs to 0.7 mmol in running dogs at 55 weeks of age and increased 63 percent from 0.8 to 1.3 mmol at 70 weeks of age, but running dogs consumed 50 percent more food, vitamin D, calcium, and phosphorus than did sedentary controls (Puustjärvi et al., 1992).

Overall, with the exception of cardiac hypertrophy and changes in bones, gross changes associated with training are comparatively subtle. Training does, however, affect the capacity to maintain exercise. Musch et al. (1985) found that oxygen consumption at any slope or speed was the same in trained and untrained 1- to 2-year-old female foxhounds running on a treadmill, but trained dogs were able to run faster on a steeper slope and their $\dot{V}O_2$max was higher. At any speed or slope, oxygen consumption, cardiac output, arteriovenous oxygen difference, mean arterial pressure, and systemic vascular resistance were unaffected by training, but heart rate was 14 beats per minute lower, stroke volume was 14 percent greater, and the increase in venous lactate concentrations was less in trained dogs than untrained dogs. Training increased $\dot{V}O_2$max by 28-31 percent because maximal cardiac output was 27-28 percent higher and maximal arteriovenous oxygen difference was 4 percent higher in trained than untrained dogs. At $\dot{V}O_2$max, postexercise venous lactate concentrations and mean arterial pressure were unchanged but systemic vascular resistance was 20-23 percent lower in trained dogs. Blood flow to the heart, diaphragm, tongue, and muscles of the hind limb increased 200-600 percent during exercise in these dogs; blood flow to nonlocomotor muscles such as the temporal muscle decreased 60 percent and blood flow to the brain was unaffected during exercise (Musch et al., 1987). Training did not alter capillary density in the muscles (Parsons et al., 1985) or blood flow to most organs, but blood flow to the large intestine, spleen, liver, adrenal glands, and kidneys decreased with exercise only in trained animals (Musch et al., 1987).

Altom (1999) reported that olfactory acuity decreased 64 percent when unconditioned 2- to 4-year-old English pointers ran 8 km·h^{-1} on a 10 percent slope for 1 hour but did not decrease during this exercise when dogs had been conditioned by running at 8 km·h^{-1} on the level for 30 minutes three times weekly for 12 weeks. Wakshlag et al. (2002a) also reported pronounced up-regulation during the hunting season of some components (the ubiquinated conjugates and p31 regulatory capping subunit, but not the catalytic core β-subunit) of the ubiquitin-proteosome pathway responsible for proteolysis in skeletal muscle of Labradors and English pointers.

Clark et al. (1988) reported that muscle phosphocreatine decreased less and isometric tension was greater during electrical stimulation of skeletal muscle previously conditioned by chronic electrical stimulation than during stimulation of unconditioned muscle. In dogs trained to run on three legs, Procter and Best (1932) found that glycogen increased in exercised muscles during the first 3 weeks of training but returned to pretraining levels if training was continued for a month. Pohoska (1979) found that confining 15- to 25-kg mongrel dogs to 0.4-m^3 cages for 2-5 months increased the rate of increase in rectal temperature and reduced the mean time to exhaustion from 197 ± 17 to 118 ± 21 minutes when dogs ran on a treadmill with a 21 percent slope at 5-6 km·h^{-1}. Confinement reduced resting muscle glycogen content by 15 percent but did not affect muscle glycogen at exhaustion. Confinement also increased the rate of decline in blood glucose during exercise, reduced the increase in FFA concentrations during exercise, increased norepinephrine concentrations during exercise, and reduced the FFA response to infused norepinephrine. These changes had almost returned to normal by 15 days after confinement ended. Nazar et al. (1992) showed that all of these changes returned to normal after 8 weeks of retraining (running at 6 km·h^{-1} on a 21 percent slope for 1 h·d^{-1}). Sneddon et al. (1989) reported that fitness deteriorated in Canaan dogs within 3-5 weeks of ceasing training.

Paul and Holmes (1973) found that plasma FFAs supplied only 20-30 percent of energy during moderate submaximal exercise (6 km·h^{-1} on a 15 percent slope) in untrained dogs but 70-90 percent of energy in trained dogs. Issekutz et al. (1964) noted that the rate of increase in blood lactate during exercise varied widely with physical condition and showed that there was a negative correlation between lactic acid concentration and the rate of FFA release during exercise. Thus, untrained animals have to use anaerobic sources of energy, which limits their stamina. Supplying glucose before, during, and after exercise may therefore be more important in untrained animals than trained animals, and the increase in stamina that Downey et al. (1980) observed in trained beagles when fat was increased in the diet may not occur in untrained dogs.

ENERGY REQUIREMENTS

Minimal Metabolism

A minimal amount of energy is required each day to maintain homeostasis even in the absence of factors that increase energy consumption such as exercise, food consumption, or a low environmental temperature. The conditions for measuring basal metabolic rate (BMR), resting fed metabolic rate (RFMR), maintenance energy requirement (MER), and their values for dogs and cats are discussed in Chapter 3; however, MER may vary with any factor that affects heat production.

Anxiety

Release of catecholamines in stressed animals increases metabolic rate. For example, when animals are placed in a chamber to measure metabolic rate, oxygen consumption is initially very high but declines over time as animals stop moving about and become accustomed to their environment. Environmental stress may, therefore, increase metabolic rate. Woods and Besch (1974), for example, report that postabsorptive heat production was higher (266 ± 24 kcal·kg BW$^{-0.75}$·d^{-1}) in dogs (greyhounds and beagles) kept in cages on their own compared to the 135 ± 24 kcal·kg BW$^{-0.75}$·d^{-1}

produced by the same dogs kept in groups of two to four. The authors speculate that isolating the dogs caused stress.

Circadian Rhythms

Besch and Woods (1977) reported that heat production varies with a circadian rhythm in dogs. Heat production in beagles and greyhounds kept in cages in a thermoneutral environment with a 12-hour dark period was low in the morning (124 ± 17 and 94 ± 17 kcal·kg $BW^{-0.75}$·d^{-1}, respectively), gradually increased to an evening maximum (195 ± 21 and 166 ± 20 kcal·kg $BW^{-0.75}$·d^{-1}, respectively), and then declined through the night. Heat production averaged 141 ± 26 and 139 ± 4 kcal·kg $BW^{-0.75}$·d^{-1} in greyhounds and beagles, but there was a 58 percent and 75 percent increase, respectively, from morning to evening. Diet-induced thermogenesis was not responsible for this oscillation because dogs were fed in the evening. Heat production was similar in dogs maintained entirely in the dark or entirely in the light (Woods and Besch, 1971), so, overall, this effect should not influence daily MER.

Cold-Induced Thermogenesis

Thermoregulation in Dogs

Warm-blooded or homeothermic animals, such as dogs and cats, increase heat production to maintain body temperature at low ambient temperatures. The ambient temperature below which heat production starts to increase is termed the lower critical temperature and appears to vary with the thickness of an animal's coat (Scholander et al., 1950b). Metabolic rate also increases in homeotherms in high ambient temperatures because cooling mechanisms require energy. The temperature above which energy consumption increases is the upper critical temperature. The range of temperatures at which normal temperatures are maintained with no increase in metabolic rate is the thermoneutral zone (Figure 11-1).

Newborn pups have a much reduced capacity to maintain body temperature and do not gain the adult capacity to thermoregulate until they are 3 weeks of age (Jensen and Ederstrom, 1955). Crighton and Pownall (1974) found that newborn pups were able to maintain body temperature only when ambient temperature was between 20 and 30°C (body temperature decreased when ambient temperature was below 20°C and increased when it was above 30°C) but there was no thermoneutral zone. Heat production was lowest (77 kcal·kg $BW^{-0.75}$·d^{-1}) at an ambient temperature of 30°C but increased linearly as ambient temperature decreased below 30°C and was double at an ambient temperature of 15°C (an increase of 5 kcal·kg $BW^{-0.75}$·d^{-1}·$°C^{-1}$ below 30°C). Heat production also increased linearly above an ambient temperature of 30°C until it was 50 percent higher at an ambient temperature of 35°C (an increase of 6

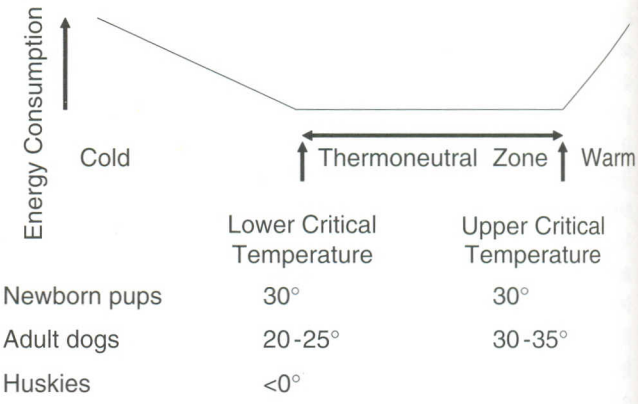

FIGURE 11-1 Effect of environmental temperature (°C) on energy requirement.

kcal·kg $BW^{-0.75}$·d^{-1}·$°C^{-1}$ above 30°C). McIntyre and Ederstrom (1958) found that newborn pups increased heat production by 25 percent at an ambient temperature of 23°C but were unable to increase their metabolic rate by more than 25 percent at an ambient temperature of 5°C, probably because they rapidly became too cold to mount a metabolic response. Only after 3 weeks of age were pups able to maintain body temperature like adults and double their metabolic rate at an ambient temperature of 5°C. Similarly, pups were not able to maintain body temperature at an ambient temperature of 40°C until 4 weeks of age (Jensen and Ederstrom, 1955). Panting, like shivering, appeared at 2-3 days of age but did not become an effective tool for losing heat until 3 weeks of age.

Hume and Egdal (1959) reported that adult dogs maintained normal body temperature in ambient temperatures as low as –46 to –50°C for 4-27 hours and six out of seven dogs maintained temperature at –75 to –79°C for 3-5 hours. Giaja (1938) found that an ambient temperature of –160° was necessary to make a dog hypothermic after 1 hour. Adult dogs tolerated high ambient temperatures up to 56°C for 3 hours or more in dry air (Adolph, 1947) but became poikilothermic at 33°C or higher in moist air (Lozinsky, 1924). Taylor et al. (1971) reported that heat production was lowest (63 kcal·kg $BW^{-0.75}$·d^{-1}) in two 3-kg dogs at ambient temperatures of 25 and 30°C and that heat production increased to 110 kcal·kg $BW^{-0.75}$·d^{-1} at a low ambient temperature of 20°C and a high ambient temperature of 40°C. Hammel et al. (1958) found that heat production in adult dogs increased linearly below a lower critical temperature of 23-25°C until it was twice BMR at 10°C (an increase of 5 kcal·kg $BW^{-0.75}$·d^{-1}·$°C^{-1}$). The upper critical temperature was between 30 and 35°C, and energy consumption increased by less than 10 percent at 35°C. Scholander et al. (1950a) reported similar results from a study by Rubner: two dogs showed a thermoneutral zone from 20 to 30°C; metabolic rate was double at 5°C, and metabolic rate increased 10 percent at 35°C. Blatteis et al. (1973) observed a 50 percent increase in heat production in adult dogs moved acutely from

an ambient temperature of 26°C to one of 6°C. Minaire et al. (1973) reported that energy utilization in the cold increased more than fourfold to approximately 487 kcal·kg $BW^{-0.75}$·d^{-1} when dogs were shorn to increase their response to the cold and were acutely exposed to air at an ambient temperature of –25°C. Lucas et al. (1980) reported that oxygen consumption increased to a maximum 10 minutes after dogs were acutely immersed in 8-13°C water. The $\dot{V}O_2$max in cold water was 3.5 ± 0.4 L O_2·kg BW^{-1}·h^{-1} (729 ± 88 kcal·kg $BW^{-0.75}$·d^{-1}), which was eightfold higher than oxygen consumption in the air at 23°C but only 60 percent of the $\dot{V}O_2$max of these dogs during exercise. Dogs were able to maintain this level of oxygen consumption provided their colonic temperature did not decrease more than 4°C.

More moderate responses have been found in dogs in kennels. Zentek and Meyer (1992) reported that MER was nearly 70 kcal ME·kg $BW^{-0.75}$·d^{-1} higher in Great Danes in outdoor kennels in winter than in summer. Since the average ambient temperature is 25°C higher in summer than winter in northern Germany, this represents a difference of approximately 3 kcal·kg $BW^{-0.75}$·$°C^{-1}$. Blaza (1982) reported a 25 percent increase in maintenance food intake in four Labrador retrievers and a beagle when ambient temperature decreased from 15 to 8°C. Nagasarka and Carlson (1965), however, found that food intake increased only 30 percent in beagles, though they lost 4 percent more body weight when kept in a room at –10°C for 1 month compared to dogs kept at 28°C. Crist and Romsos (1987) found a 38 percent increase in energy expenditure in overfed adult beagles after 4 weeks' exposure to an ambient temperature of 3°C compared to overfed dogs at 22°C. Not surprisingly, continuous exposure to cold increases energy requirements more than intermittent exposure: Davis (1967) noted that continuous exposure to an ambient temperature of 5°C caused clipped dogs to lose body weight, whereas clipped dogs maintained their body weight when exposed to –10°C for only 8 hours daily.

The thickness of a dog's fur may also affect energy requirements in the cold. Hoesslin (1888) estimated that the metabolic rate of a puppy raised at an ambient temperature of 5°C was only 12 percent higher than that of a litter mate raised at an ambient temperature of 32°C, but the coat of the dog raised in the cold was almost four times as thick. Scholander et al. (1950a) reported that the metabolic rate of two Eskimo dog pups varied very little at ambient temperatures from –30 to 40°C. Finke (1991) also reported that as ambient temperature declined from 20 to 0°C, the maintenance ME intake of Siberian huskies (125 kcal ME·kg $BW^{-0.75}$·d^{-1}) did not increase significantly, whereas the maintenance ME intake of beagles and Labrador retrievers increased by 20-25 percent (approximately 1 kcal ME·kg $BW^{-0.75}$·d^{-1}·$°C^{-1}$). Nevertheless, Durrer and Hannon (1962) suggest that energy consumption increased by approximately 3 kcal·kg $BW^{-0.75}$·d^{-1}·°C in both huskies and beagles (from 120 to 205 kcal·kg $BW^{-0.75}$·d^{-1}·$°C^{-1}$, from 162 to 177 kcal·kg $BW^{-0.75}$·d^{-1}, respectively) as ambient temperature decreased from 14°C in summer to –20°C in winter. Orr (1966) reported that tethered sled dogs in Antarctica lost only small amounts of weight when consuming 166 kcal ME·kg $BW^{-0.75}$·d^{-1} at temperatures estimated by Campbell and Donaldson (1981) to be 0-10°C. Campbell and Donaldson (1981), however, reported that dogs consuming 320 kcal ME·kg $BW^{-0.75}$·d^{-1} maintained body weight at –30°C in a tunnel (no wind chill) but lost weight when exposed to a wind of 6 m·s^{-1}. More recently, Hinchcliff et al. (1997b) found that sled dogs consumed 130 ± 29 kcal ME·kg $BW^{-0.75}$·d^{-1} in kennels in a thermoneutral environment (20°C) but expended 263 ± 96 kcal·kg $BW^{-0.75}$·d^{-1} at –10 to –35°C.

Metabolic rate, therefore, appears to increase above basal by 5 kcal·kg $BW^{-0.75}$·d^{-1}·$°C^{-1}$ (a 100 percent increase at 5°C) in inactive dogs below their critical temperature. The cold-induced increase in heat production was more muted (≤ 3 kcal·kg $BW^{-0.75}$·d^{-1}·$°C^{-1}$ or a 50 percent increase at 5°C) in active animals, such as dogs in kennels, because heat production in active dogs is higher than basal even in a thermoneutral environment. The metabolic response to cold also develops at a lower ambient temperature in dogs such as huskies with a critical temperature that is lower than that of other breeds. The lower critical temperature appears to be 30°C for newborn pups, 20-25°C for most adult dogs, and probably less than freezing for sled dogs. Wind chill, clipping the coat, and immersion in cold water cause a greater response to cold. The $\dot{V}O_2$max in cold water is 30 kcal·kg $BW^{-0.75}$·h^{-1}. The upper critical temperature is 30°C for pups and between 30 and 35°C for adult dogs. The metabolic rate increases at an ambient temperature of 35°C by 50 percent in pups and 10 percent in adults.

Nonshivering Thermogenesis and Cold Acclimatization

Shivering is the most important mechanism for increasing metabolic rate in the cold, but nonshivering heat production increases and shivering decreases during prolonged exposure to cold in many species (Jansky et al., 1969). Brown adipose tissue is the most important site of nonshivering thermogenesis in rats. Holloway et al. (1985) and Ashwell et al. (1987) found that the fat in neonatal beagle pups had the character of brown adipose tissue (high cytochrome oxidase activity, densely populated with mitochondria, and presence of uncoupling protein), but fat in dogs older than 6 months of age had the character of white adipose tissue (few mitochondria and less cytochrome oxidase). This white adipose tissue retained an ability to increase oxygen uptake in response to norepinephrine however, and chronic administration of a β-agonist to mimic chronic cold exposure caused fat depots other than subcutaneous fat to become more like brown adipose tissue. Davis (1967) showed that nonshivering thermogenesis also occurs in the skeletal muscle of cold-acclimatized dogs.

In some but not all species, this nonshivering thermogenesis develops as a result of increased sensitivity to norepinephrine (Jansky et al., 1969). Nonshivering thermogenesis developed in clipped dogs exposed to –10°C for 8 hours daily for 6-8 weeks (Davis, 1967) or immersed in 3-8°C water for 1 hour daily for 10 days (Therminarias et al., 1979) and in unclipped dogs exposed to –10°C continuously for 1 month (Nagasarka and Carlson, 1965). The plasma concentrations of triiodothyronine increased during cold adaptation, but the increase in plasma catecholamine concentrations in response to cold and the increase in metabolic rate in response to infused catecholamines were much reduced in cold-adapted dogs (Nagasarka and Carlson, 1965; Therminarias et al., 1979; Minaire et al., 1983). Increased sensitivity to catecholamines is not responsible therefore for the increase in nonshivering thermogenesis observed in cold-adapted dogs.

Energy consumption in a thermoneutral environment was unaffected by cold-adaptation, but maximal heat production during immersion in cold water increased 40 percent (from 655 to 881 kcal·kg $BW^{-0.75}$·d^{-1}) in cold-adapted dogs and they were able to maintain body temperature more effectively than warm-adapted dogs (Therminarias et al., 1979). Long-term adaptation to cold, therefore, does not appear to affect energy requirements at any ambient temperature but does improve a dog's ability to respond to and tolerate cold. Such changes are not dissimilar to the changes in metabolic response to exercise observed in dogs during training.

Thermoregulation in Cats

There is much less information concerning thermoregulation in cats. Adolph (1951) reported that newborn kittens were able to tolerate lower body temperatures than adult cats. Scholander et al. (1950a) reported a study by Theodor of one cat that suggests a thermoneutral zone from 20 to 30°C and a 30 percent increase in metabolic rate at –5°C. Forster and Ferguson (1952) found that cats became vasoconstricted at 24-27°C, and became more active below 20°C; piloerection occurred below 10°C and shivering only began below 5°C; rapid breathing and panting, however, were noted in a warm environment of 36-40°C. Jacobson and Squires (1970) conducted experiments to assess the effect of artificially altering the hypothalamic temperature of two cats in different ambient temperatures. At normal hypothalamic temperatures, mean oxygen consumption was at a minimum (40 kcal·kg BW^{-1}·d^{-1}) above an ambient temperature of 30°C and increased by 50 percent at normal room temperature (25°C) and by 150 percent at 5°C. Panting and respiratory water loss increased in a warm environment (36°C), but there was little or no increase in oxygen consumption. Doris and Baker (1981) reported that the mean metabolic rates of cats was lowest at 38°C and approximately 30 percent higher at 35 and 43°C, and that evaporative losses increased above 35°C. Adams et al. (1970) reported that the energy consumption of adult shorthaired unacclimatized cats was approximately 73 kcal·kg BW^{-1}·d^{-1} at 35 and 38°C but increased linearly by approximately 5 kcal·kg BW^{-1}·d^{-1}·$°C^{-1}$ below and above this range to 152 kcal·kg BW^{-1}·d^{-1} at 20°C and 86 kcal·kg BW^{-1}·d^{-1} at 41°C. Tissue insulation of the extremities increased below 35°C, and evaporative losses and respiration increased markedly above 35°C. Measurements in chambers used for indirect calorimetry do not allow full expression of behavioral patterns that may extend the thermoneutral zone, but results suggest that there is a relatively narrow thermoneutral zone in adult unacclimatized cats that is above 30-35°C and below 38°C. They also suggest that there may be a substantial thermoregulatory component to heat production at normal room temperature in cats, which may explain why measurements of metabolic rates in cats have often varied substantially in different laboratories.

Other studies have used metabolic rate at normal room temperature (25°C) as a baseline (Table 11-4). In these studies, energy consumption increased approximately 60 percent (in some studies as much as 160 percent) when adult cats moved from room temperature (25°C) to an ambient temperature of 0-10°C. Energy consumption also increased 60 percent in kittens, but this was associated with a smaller decline in ambient temperature (from 30 to 20°C).

Shivering increased linearly with energy consumption and was responsible for 80 percent of heat production in cats during acute cold exposure (Hemingway et al., 1964; Hoenig and Ferguson, 2002). Hemingway and Stuart (1962), however, reported a 30-40 percent increase in metabolic rate in the absence of shivering in cats acclimatized for 1 month at 0-5°C but not in cats acclimatized at temperatures above 10°C. This nonshivering thermogenesis was associated with an increased metabolic response to norepinephrine in cold-acclimatized cats, but the increase in sensitivity to norepinephrine was less than in rats (Hemingway et al., 1964). Adams (1963) also found a small increase in metabolic rate in cats that had acclimatized at 5°C for 2 months.

In summary, therefore, the lower and higher critical temperature of unacclimatized adult cats lies between 30-35 and 38°C, and the metabolic rate increases above and below these temperatures by as much as 5 kcal·kg $BW^{-0.67}$·d^{-1}·$°C^{-1}$. This represents a two- to threefold increase at near freezing temperatures. The cold-induced increase in heat production may be more muted (≤ 3 kcal·kg $BW^{-0.67}$·d^{-1}·$°C^{-1}$) in active animals.

Fuels for Thermogenesis

Dogs

In dogs, the changes in metabolism in response to the increased energy demands during exposure to cold are similar to the changes observed in response to the energy demands of endurance exercise (Minaire et al., 1973). Paul and

TABLE 11-4 Effect of Changes in Ambient Temperature on Energy Utilization[a] in Acclimatized and Unacclimatized Cats

Subjects	*n*	BW (kg)	Ambient Temperature (°C)	Daily Energy Utilization (mean ± 2 SD) (kcal·kg BW^{-1})	(kcal·kg BW$^{-0.67}$)	Reference
Unacclimatized cats	6		25-28	52 ± 22		Stuart et al., 1961
			0-5	140 ± 53		
Adult male or female intact cats	5	2-3				Adams, 1963
Unacclimatized (at 25°C)			23	86	117[b]	
			10	144	195[b]	
			0	168	228[b]	
Acclimatized at 5°C			23	90	122[b]	
			10	140	190[b]	
			0	187	254[b]	
Adult female, intact short-haired cats	5	2.0-3.33	41	86[b]	118	Adams et al., 1970
			38	73[b]	100	
			35	73[b]	100	
			32	87[b]	120	
			29	98[b]	135	
			26	116[b]	160	
			23	138[b]	189	
			20	152[b]	210	
Unacclimatized adult cats	2	2.36[c]	36 ± 3	52 and 35	69[c]	Jacobson and
			31 ± 1	45 and 35	60[c]	Squires, 1970
			25 ± 1	69 and 55	92[c]	
			5 ± 3	104 and 90	138[c]	
Adult domestic male and female cats after 2-3 days of acclimatization	9	2.8-4.6	43	47	74[b]	Doris and Baker, 1981
			40	38	59[b]	
			38	33	52[b]	
			35	43	67[b]	
Unacclimatized adult female and male cats	4	3.0-4.4	24-27	53 ± 4	83 ± 14	Gautier et al., 1989
			3-8	86 ± 21	136 ± 46	
Unacclimatized 2-day-old kittens	9	155 ± 24 g	30	166 ± 42	89[b]	Mortola and
			20	270 ± 83	145[b]	Matsuoka, 1993

[a]Measured as oxygen consumption using indirect calorimetry.
[b]Value is approximate as it has been calculated using the mean body weight or the midpoint between maximum and minimum body weights.
[c]Weight of only one cat was reported.

Holmes (1973, 1975) reported that, when dogs were acutely exposed to an ambient temperature of 4-5°C for 120 minutes, energy expenditure increased 40 percent but the energy derived from FFA increased from 32 ± 4 percent at rest to 48 ± 4 percent in the cold. Serum FFA concentrations increased 70 percent, FFA turnover increased 60 percent, and the percentage of FFA that was immediately oxidized increased from 22 to 33 percent. In adult mongrel dogs, $\dot{V}O_2max$ was 40 percent less in the cold than during exercise, but plasma norepinephrine and epinephrine concentrations increased to the same degree; plasma lactate and glucose concentrations both increased in the cold and during exercise, but blood glucose was 45 percent higher and lactate was 48 percent lower in the cold; and FFA concentrations increased 43 percent in the cold but not during maximal exercise (Lucas et al., 1980). In adult mongrel dogs shorn to increase the response to cold and acutely exposed to temperatures as low as –25°C, energy consumption increased fourfold or more; plasma FFA concentrations almost doubled; FFA turnover and oxidation rates increased four- and eightfold, respectively; and the contribution of FFAs to carbon dioxide production nearly doubled from 36 to 64 percent or more (Vincent-Falquet et al., 1972; Minaire et al., 1973). Plasma concentrations of β-hydroxybutyrate doubled in the cold,

probably because of increased generation of ketones from FFAs in the liver (Minaire et al., 1982). Glucose turnover doubled and glucose oxidation rate increased fourfold, but plasma glucose concentrations did not decline because glucose formation from muscle glycogen and from glycerol in FFAs increased and the contribution of glucose to carbon dioxide production declined slightly from 19 percent to 12 percent (Pernod et al., 1972; Minaire et al., 1973). Glucose utilization, therefore, remained high despite high rates of lipolysis in the cold, as it does during exercise. Alanine clearance increased but plasma alanine concentrations declined in the cold, which suggests that, despite an increased requirement for glucose and increased glucose utilization, pyruvate generated by glycolysis was being oxidized rapidly in the cold and diverted from alanine synthesis (Minaire et al., 1982). Lactate production by glycolysis increased in the cold, but blood lactate concentrations remained low because lactate oxidation also increased (Minaire et al., 1971).

These changes are consistent with skeletal muscle being the primary source of increased energy consumption in the cold as well as during exercise. Minaire et al. (1973) even suggested that glycogen stores may limit the ability to withstand cold as well as limiting stamina during exercise. Currently, there have been no studies of the influence of changing the relative proportions of the macronutrient composition of the diet on resistance to cold in dogs. Nevertheless, if glycogen availability limits a dog's ability to withstand the cold, then diets containing increased fat may improve the capacity of dogs to withstand the cold by reducing glycogen utilization in the same fashion that stamina increases in exercising dogs fed high-fat diets. It is also possible that dogs undertaking endurance exercise in warm environments may require less fat during periods of quiescence and, therefore, may need slightly less fat in their diets than dogs exposed to very low temperatures between bouts of exercise.

It has not been determined if the requirements for protein or micronutrients change in dogs in the cold. Blood glucose does not decline in the cold as it does during endurance exercise; so, the demand for amino acids as precursors for gluconeogenesis is probably not as great as during exercise. Exposure to cold may increase the amino acid requirement slightly to accommodate hair growth and synthesis of mitochondria and enzymes in adipose tissue during cold adaptation, but an increase in urinary excretion of nitrogen has not been found in other species exposed to cold (Blaxter, 1989). The requirements for protein, vitamins, and most minerals are probably similar in animals kept in the cold, therefore, to those kept in a thermoneutral environment.

Cats

Reducing the ambient temperature did not affect RQ in adult cats moving from room temperature (25°C) to 3-8°C (Gautier et al., 1989) or in kittens moving from 30 to 20°C (Mortola and Matsuoka, 1993), despite a 60 percent increase in metabolic rate. This suggests that substrate utilization in cats may not change during exposure to cold.

Nutrients in a Warm Environment

There appear to be no studies of the metabolic response of dogs to high ambient temperature. The heat increment of protein is greater than that of carbohydrate and fat (Blaxter, 1989). High-protein meals will tend to generate slightly more heat postprandially than low-protein meals, but the effect on daily heat production is likely to be very small because the heat increment of a meal is small. Any advantage of feeding a low-protein diet in a warm environment should be trivial.

Effect of Reduced Oxygen at High Altitude

With increasing altitude, the fractional concentration of oxygen in inspired air remains 21 percent ($Fio_2 = 0.21$), but barometric pressure, and therefore available oxygen, decline. Barometric pressure and available oxygen are 17 percent less at an altitude of 1,500 m than at sea level, 30 percent lower at an altitude of 2,750 m than at sea level (equivalent to an Fio_2 of 0.15 at sea level), and 50 percent lower at an altitude of 5,800 m than at sea level (equivalent to an Fio_2 of 0.10 at sea level).

Piiper et al. (1966) reported that the mean energy required for standing in adult mongrel dogs decreased 10 percent at an Fio_2 of 0.11, but statistically this did not differ significantly from the energy for standing at an Fio_2 of 0.21. These authors also reported that the energy required for running each kilometer on a 10 percent slope was unaffected by reducing the Fio_2 to 0.11 but that $\dot{V}o_2max$ was at least 25 percent lower at an Fio_2 of 0.15 and at least 50 percent lower at an Fio_2 of 0.11. Schilling et al. (1956) found that the energy required for running at any speed or slope on a treadmill, whether measured at an $Fio_2 = 0.21$ or an $Fio_2 = 0.10$, was unaffected in adult dogs by 5 months of acclimatization to an Fio_2 of 0.10. Zinker et al. (1995) reported that glucose disappearance increased 50 percent at rest and during exercise in dogs when Fio_2 was decreased from 0.21 to 0.10, but arterial glucose concentration was unchanged because hepatic glucose production increased proportionately. Limb glucose and pyruvate oxidation doubled and limb glycogenolysis increased more than twofold at rest and during exercise when Fio_2 was decreased, and the fraction of carbon dioxide from lactate and glucose increased proportionately. Reducing inspired oxygen, therefore, increases carbohydrate oxidation and increases carbohydrate mobilization in the liver and muscle while decreasing fat metabolism. Stamina is probably less therefore at high altitudes, and the benefit of feeding a high-fat diet may also be reduced. Cold-induced thermogenesis, shivering, and the ability to maintain body temperature at 6°C were also inhibited

in adult dogs by acute exposure to an Fio_2 of 0.12, although there was a slight recovery of heat production after 3 hours exposure to hypoxia (Blatteis and Lutherer, 1973).

In adult cats at normal room temperature (23-27°C), energy consumption decreased by 20 percent during acute exposure to hypoxia ($Fio_2 = 0.10$), but there was partial recovery and the decrease was only 10 percent after 1-hour exposure to hypoxia (Gautier et al., 1989). Hypoxia ($Fio_2 = 0.10$) caused a more marked (30 percent) decrease in oxygen consumption and a 30 percent decrease in shivering in these cats during acute exposure to 3-8°C. In kittens, hypoxia ($Fio_2 = 0.10$) decreased energy consumption by 40 percent at an ambient temperature of 30°C and by 50 percent at an ambient temperature of 20°C (Mortola and Matsuoka, 1993). Nevertheless, physiologic compensation during acclimatization and the rapid recovery in response to prolonged hypoxia of only a few hours observed in these experiments suggest that altitude may cause only a very small decrease in heat production in either dogs or cats whether in a thermoneutral environment or in the cold.

EFFECT OF EXERCISE ON ENERGY REQUIREMENTS

The MER of a dog or cat may be considered to be composed of the energy required in the absence of exercise plus the energy associated with spontaneous exercise. How energy requirements vary with exercise is the subject of this discussion. Of the energy required in the absence of exercise, BMR, diet-induced thermogenesis, and RFMR are discussed in Chapter 3; cold-induced thermogenesis is discussed earlier in this chapter.

Effect of Exercise on Energy Required in the Absence of Exercise

Steinhaus (1928) reported that BMR was unaffected by six months of training in previously confined mongrel dogs, which ran 20-80 $km \cdot week^{-1}$ on a 22 per cent slope at 8 $km \cdot h^{-1}$. The effect of exercise on dietary thermogenesis is less clear. Both Rubner (1910) and Anderson and Lusk (1917) reported that, when a single dog was exercised after a high-protein meal, the specific dynamic effect of the meal was unchanged and there was an exact summation of the energy increments due to diet and exercise. Anderson and Lusk (1917) also reported, however, that the specific dynamic effect of carbohydrate was abolished when exercise was performed immediately after ingestion of 0.8g·kg BW^{-1} of glucose, possibly because the glucose was used immediately without prior conversion to glycogen or fat. Exercise does not appear to affect dietary thermogenesis in sheep and humans (Blaxter, 1989).

Ambient temperature must be taken into account only when assessing the energy required in the absence of exercise in dogs exercising in a cold environment. Cold-induced thermogenesis is of little consequence in animals that live indoors in a fairly stable ambient temperature or in dogs running on treadmills at room temperature. Even in a very cold environment however, cold-induced thermogenesis is only of consequence during periods when dogs or cats are not exercising. Heat produced by muscular activity is much greater than that necessary to maintain body temperature. Heat loss, not retention of heat is therefore of primary importance during exercise.

Energy Required for Exercise: Dynamic Exercise (Short Runs) Versus Steady-State Exercise (Long Runs)

Most studies have measured the energy requirements of dogs running long distances using aerobic sources of energy. During this endurance exercise, oxygen consumption is in a steady-state equilibrium with energy expenditure and can be used to measure energy expenditure. Only a few studies have attempted to assess energy requirements of dogs running short distances using both aerobic and anaerobic sources of energy. Anaerobic energy consumption is difficult to measure because it represents a "debt" that subsequently has to be repaid. This debt has two components: an "alactacid" debt and a lactic acid debt (Staaden, 1984).

Alactacid Debt

Marconi et al. (1982) showed that when 15 to 17 kg mongrel dogs started to run on a 10 percent slope, there was a slight delay of 2 minutes before oxygen consumption reached a new equilibrium with energy expenditure and there was a similar delay of 3 minutes before oxygen consumption returned to resting levels when running stopped after a 5-minute run. The delay at the start of exercise created an oxygen debt that was repaid at the end of exercise. *This delay did not represent a lactic acid debt because blood lactic acid concentrations remained close to resting levels.* This delay represented an alactacid debt acquired as oxygen stores desaturated at the start of exercise and as adenosine triphosphate (ATP) and creatine phosphate provide energy from high-energy phosphate bonds. The accumulation and repayment of this alactacid debt showed first-order kinetics with short half-times (20 ± 2 seconds and 24 ± 3 seconds, respectively), which were unaffected by the speed of running.

The energy consumed in generating the debt can be estimated from the oxygen consumed (area under the curve) during recovery (Figure 11-2). The area under a curve can be obtained by integration. Integration of the first order recovery curve gives the oxygen consumption during recovery (mL $O_2 \cdot kg\ BW^{-1}$) as the oxygen consumption at the end of steady-state exercise (mL $O_2 \cdot kg\ BW^{-1} \cdot s^{-1}$) divided by an elimination constant λ, where λ is (ln 2)/(the half-time) (Gibaldi and Perrier, 2001). In this instance, λ is 0.693/24 seconds. For dogs undertaking the highest $\dot{V}O_2max$ ever reported (2.9 mL $O_2 \cdot kg\ BW^{-1} \cdot s^{-1}$) (Reynolds et al., 1999), the

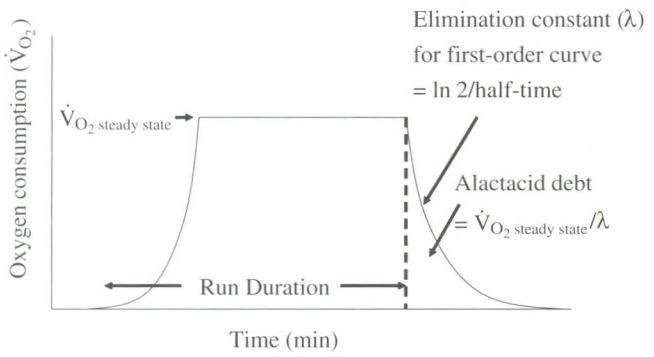

FIGURE 11-2 Changes in oxygen consumption before and after a short bout of submaximal exercise.

oxygen consumption during recovery would be 2.9 × 24/0.693 or 100 mL O_2·kg BW^{-1}. Assuming 5 kcal·L^{-1} O_2, this would give a maximum for oxygen replenishment during recovery of 0.5 kcal·kg BW^{-1} in dogs. This is very small and of consequence only during brief exercise; when averaged over a run of more than a few minutes, this alactacid debt can be ignored. The prolonged excess post-exercise oxygen consumption (EPOC) observed in humans for up to 24 hours after long bouts of strenuous exercise (Bahr, 1991) has yet to be described in dogs.

Lactic Acid Debt During Submaximal Exercise

Seeherman et al. (1981) reported that lactic acid increased at the start of exercise to less than 10 mmol·L^{-1} in dogs but then declined to resting levels in dogs exercising at 78 percent $\dot{V}O_2$max or remained unchanged for the duration of the run in dogs exercising at 94 percent $\dot{V}O_2$max. Young (1959) found that blood lactate concentrations did not differ from resting concentrations in beagles at the end of exhaustive exercise at 50 percent $\dot{V}O_2$max (6 km·h^{-1} on a 17 percent slope). Brzezinska et al. (1980) reported that mean lactate concentrations increased gradually from 1.4 mmol·L^{-1} at rest to 2.7 mmol·L^{-1} at the point of exhaustion. Wagner et al. (1977) reported that mean arterial lactate concentrations increased to less than 3 mmol·L^{-1} and dogs became alkalotic with a mean arterial pH of 7.55 (probably a respiratory alkalosis associated with panting) after running for more than 20 minutes at 50 percent $\dot{V}O_2$max (8 km·h^{-1} on a 50 percent grade). Cerretelli et al. (1964) also reported no lactic acid production in dogs running on a level treadmill but found that blood lactic acid concentrations increased gradually in dogs running at speeds greater than 8 km·h^{-1} on a 10 percent slope and increased 1.6 mmol·L^{-1}·min^{-1} in dogs running at 16 km·h^{-1} on a 10 percent slope, even though oxygen consumption had not reached a maximum. Depocas et al. (1969) found that blood lactate concentrations did not change greatly in dogs running at 30 percent $\dot{V}O_2$max but the turnover rate and rate of oxidation of lactate increased two- and fourfold, respectively.

Cerretelli et al. (1969) estimated that the mean energy provided by lactic acid in canine gastrocnemius muscle was 22.6 cal·$mmol^{-1}$ during initial work but only 19.7 cal·$mmol^{-1}$ in fatigued muscle. Piiper et al. (1966) estimated that lactic acid provided 20 cal·$mmol^{-1}$ in dogs running in a reduced oxygen atmosphere. A value of 21 cal·$mmol^{-1}$ for the energy from lactate seems a reasonable midpoint. Total lactic acid accumulation can be estimated by assuming that the peak arterial lactic acid concentration measured 5-10 minutes after exercise is representative of lactic acid distributed uniformly in the total body water (Cerretelli et al., 1964). Staaden (1984) reported that the arterial blood lactate concentration in greyhounds was 1.13 times the venous lactate concentration. The total body water of beagles measured by desiccation varied with age and amount of fat mass from 50 to 80 percent of body weight (Sheng and Huggins, 1971, 1979). Plasma is 91 percent water (Hawk et al., 1954). Multiplying venous lactate concentration by 1.13 (to obtain arterial concentrations) and by total body water fraction (0.5 to 0.8) and dividing by 0.91 (plasma water fraction) gives an estimate of total lactate. Thus, lactate would provide between 13 and 21 cal·kg BW^{-1} for each millimole per liter of lactate venous blood. Since dogs develop no more than 10 mmol·L^{-1} lactate in venous blood during submaximal runs, the maximal energy from lactate would be less than 210 cal·kg BW^{-1}, which is small enough to be ignored when averaged over a run of more than 15-20 minutes.

Lactic Acid Debt During Supramaximal Exercise

Anaerobic metabolism with accumulation of lactic acid is of greater consequence in dogs undertaking supramaximal sprint exercise over short distances. Seeherman et al. (1981) reported that animals refused to continue supramaximal exercise when lactate concentrations reached 18 mmol·kg^{-1}. Greyhounds develop a marked lactic acidosis, with mean pH falling from approximately 7.4 before racing to as low as 7.0 after racing and mean blood lactate concentrations increasing from 1 mmol·L^{-1} or less before racing to 24-34 mmol·L^{-1} after racing (Rose and Bloomberg, 1989; Ilkiw et al., 1989; Nold et al., 1991; Pieschl et al., 1992; Hill et al., 2000, 2001b). Lactate concentrations reach a peak, and pH reaches a trough 2-10 minutes after a sprint; lactate returns to normal and pH increases to slightly above normal by approximately 30 minutes after a sprint (Staaden, 1984; Snow et al., 1988; Rose and Bloomberg, 1989; Pieschl et al., 1992). Matwichuk et al. (1999) surprisingly reported mean blood lactate concentrations increased to only 4 mmol·L^{-1} and mean pH increased slightly to 7.6 in Labrador retrievers immediately after 10 minutes of repeatedly retrieving a soft plastic tube over a distance of 40 m, suggesting that this par-

ticular retrieving exercise involved primarily aerobic not anaerobic metabolism.

Energy Required for Short Supramaximal Exercise

Seeherman et al. (1981) reported that oxygen consumption increased linearly with speed and was proportional to distance traveled until it reached a maximum, whereupon it remained constant as speed increased. Lactate concentrations increased linearly with speed above this $\dot{V}O_2max$, which suggests that energy use continues to increase linearly with speed and is proportional to distance traveled above $\dot{V}O_2max$.

Staaden (1984) used indirect calorimetry to measure energy utilization of greyhounds running on a treadmill. He made the following assumptions: (1) oxygen consumed during a run represented 5 kcal·L^{-1} O_2 because carbohydrate would be the principal energy source; (2) oxygen replenishment measured as the persistence of oxygen utilization above resting after dogs finished running also represented 5 kcal·L^{-1} O_2; (3) the energy required to replenish high-energy phosphate bonds in ATP and creatine phosphate was 56 cal·kg BW^{-1}; and (4) lactic acid provided 21 cal·$mmol^{-1}$. Pyruvate accumulation was not taken into account, but energy from pyruvate was probably not more than one-third that from lactate (Cerretelli et al., 1964). Staaden also appears to have calculated the energy from lactate by assuming that lactate is evenly distributed throughout the whole body, not just in the total body water as recommended by Cerretelli et al. (1964). The total body water of trained greyhounds was reported recently to be 70 percent of total body weight by deuterium dilution (Hill et al., 2001b), but deuterium dilution overestimates total body water measured by desiccation by 14 percent (Sheng and Huggins, 1971). Staaden's results have been recalculated, therefore, by assuming a total body water that is 56 percent of total body weight and a water content of plasma of 91 percent (Hawk et al., 1954; Table 11-5).

The major conclusions that can be drawn from Staaden's work have not changed however. Greyhounds used a tremendous amount of energy (3 kcal·kg BW^{-1}·km^{-1}) during their initial acceleration, but energy utilization during the remainder of the run was 1 kcal·kg BW^{-1}·km^{-1}, which is similar to the rate of energy utilization during steady-state submaximal exercise for dogs of this size (discussed later). Greyhounds accelerated to their top speed of 72 km·h^{-1} and then slowed during the rest of their run. When corrected for changes in kinetic energy during the initial acceleration and during subsequent slowing, the cost of running was almost constant (1.1 kcal·kg BW^{-1}·km^{-1}) throughout a run.

Anaerobic sources of energy provided 89 percent of the energy during the initial 7.5 seconds and probably all of the energy for the initial acceleration, but all of the energy from phosphagens and the alactacid component of the debt was used within the first 15 seconds of a run. Aerobic energy sources contribute almost no energy for the first few seconds, but oxygen consumption increased to a maximum of 8.3 L O_2·kg BW^{-1}·h^{-1} between 30 and 45 seconds of a run. This $\dot{V}O_2max$ is similar to that reported in other dogs running on a treadmill (discussed later). Aerobic sources provided 37 percent of energy during a 30-second run, which is somewhat analogous to a 500-m race, and 52 percent of energy during a 60-second run, which is somewhat analogous to a 900-m race. Staaden assumed that only carbohydrate was used as an aerobic substrate during such vigorous exercise. Wiebel et al. (1996) reported that carbohydrate was the primary fuel but that fat was also used in dogs running at 80 percent $\dot{V}O_2max$. Fat may, therefore, have contributed some energy even for these short runs, but the estimate of aerobic energy use would not have been affected greatly.

Surprisingly, some reserve capacity for generating energy from lactic acid was found by Staaden after the initial burst. Nold et al. (1991) also reported that lactate concentrations increased more in greyhounds after a 704-m race than after a 402-m and 503-m race. The mean peak blood lactate concentrations reported by Staaden (16 mmol·L^{-1} after a 30-

TABLE 11-5 Rate of Energy Utilization in Greyhounds

	Segment of Run (s)				
	0-7.5	7.5-15	15-30	30-45	45-60
Distance (m)					
Per segment	100	130	222	198	165
Cumulative	100	230	452	650	815
End segment velocity (km·h^{-1})	68	64	54	44	38
Total energy cost per segment (kcal·kg BW^{-1}·km^{-1})	2.84	1.02	1.00	1.01	0.82
Rate of energy generation per segment (kcal·kg BW^{-1}·min^{-1})					
Aerobic	0.24	0.52	0.58	0.69	0.40
Lactate	1.06	0.30	0.31	0.11	0.14
Oxygen stores	0.52	0.24	0	0	0
ATP or creatine phosphate	0.45	0	0	0	0

SOURCE: Adapted from Staaden, 1984.

second run and 22 mmol·L^{-1} after a 60-second run) were lower, however, than the 24-34 mmol·L^{-1} that has been reported elsewhere after races of similar duration (Lassen et al., 1986; Rose and Bloomberg, 1989; Hill et al., 2000, 2001b). Staaden reported that not all greyhounds could sustain their best speed when running on the treadmill, and it is likely that lactic acid plays a more prominent role early in a race when dogs compete on a track.

Staaden's study also showed that greyhounds use very little energy during a race. During a 60-second run dogs consumed only 1 kcal·kg BW^{-1}. Most of this energy, 0.3 kcal·kg BW^{-1}, was consumed in the first 100 m and dogs then consumed approximately 0.1 kcal·kg BW^{-1} for each of the remaining 100 m. It is likely that dogs running on a soft, uneven track, competing against each other, and having to turn corners consume slightly more energy, but the difference is probably small because lactate accumulation and oxygen utilization are close to maximal. Even if racing dogs accumulate more lactic acid (28 mmol·L^{-1}) after a 400-m race (Rose and Bloomberg, 1989; Hill et al., 2000), lactic acid could provide only 0.4 kcal·kg BW^{-1}. The highest reported $\dot{V}O_2$max in dogs is 10.6 L O_2·kg BW^{-1}·h^{-1} (Reynolds et al., 1999), which is only 25 percent higher than the value reported by Staaden. Increasing Staaden's estimate for aerobic energy by 25 percent gives only 0.3 kcal·kg BW^{-1} for the first 30 seconds. Staaden used conservative estimates for phosphagen replenishment, but even his most liberal estimate was only 50 percent higher (0.1 kcal·kg BW^{-1}). It is also possible that Staaden underestimated oxygen replenishment. Staaden noted that oxygen consumption reached a plateau soon after the end of a run but that the plateau was higher than the resting rates of oxygen consumption. This persistent increase in oxygen consumption has bedeviled many estimates of oxygen replenishment. Most authors, like Staaden, have chosen to ignore this persistent increase, but most of the area under a first-order curve is in the tail. As discussed earlier however, the area under a first-order curve can be calculated once the half-life is known. Based on the half-life provided by Marconi et al. (1982), the maximal energy for oxygen replenishment would be 0.5 kcal·kg BW^{-1}. In total, this gives a theoretical maximum for available energy during the first 30 seconds of a run of approximately 1.3 kcal·kg BW^{-1} (39 kcal for a 30-kg greyhound running a 500-m race). Using similar logic, the maximal available energy for a 60-second race would be 1.7 kcal·kg BW^{-1} (51 kcal for a 30-kg greyhound running a 900-m race).

Energy Required for Standing and for Running on a Treadmill

Most measurements of energy consumption during exercise in dogs have been performed using indirect calorimetry with dogs in a steady-state equilibrium either standing or running long distances on a treadmill. These experiments have shown that oxygen consumption increases linearly with speed in most running mammals until it reaches a maximum ($\dot{V}O_2$max; Taylor et al., 1982). The *y*-intercept, where speed is zero, represents the energy required for standing still (Figure 11- 3). The slope is the energy required per distance traveled and is constant irrespective of velocity below the $\dot{V}O_2$max in most species (Schmidt-Nielsen, 1984; Blaxter, 1989). Taylor et al. (1982) found that in 62 species of birds and mammals, including dogs and cats, the energy required for standing (*y*-intercept) and for running declined with body weight. The energy required for standing was 124 kcal·kg BW$^{-0.7}$·d^{-1}; the energy required for running (slope) was 2.6 kcal·kg BW$^{-0.68}$·km^{-1}. In domestic animals, the cost of standing was 113 kcal·kg BW$^{-0.66}$·d^{-1} and the cost of running was 2.9 kcal·kg BW$^{-0.67}$·km^{-1}. Cohen et al. (1978), using a slightly larger data set, found that the cost of running was 2.9 kcal·kg BW$^{-0.67}$·km^{-1} for all species. Schmidt-Nielsen (1984) has suggested on theoretical grounds that the mass exponent for the cost of running should be 0.67.

Reported values for the cost of standing and running in dogs are listed in Table 11-6. The cost of standing and running declines with body weight. The cost of running, for example, appears to be higher (>1.5 kcal·kg BW^{-1}·km^{-1}) in dogs weighing less than 10 kg BW and lower (approximately 1 kcal·kg^{-1}·km^{-1}) in dogs weighing more than 10 kg. The exception is one study by Ordway et al. (1984), which gives very high values for the cost of standing and running. Regression of the mean data points, other than those given by Ordway, suggests that the cost of standing is 137 (range 102-196) kcal·kg BW$^{-0.67}$·d^{-1} and the cost of running is 1.5 (range 1.2-2.0) kcal·kg BW$^{-0.81}$·km^{-1} in dogs. The exponent for standing is the same as the interspecies exponent, whereas the exponent for running is higher than the interspecies exponent. The mean cost of standing was higher than the interspecies mean, and the cost of running was lower than the interspecies mean. With an exponent of 0.75, the mean cost of standing was 111 kcal·kg BW$^{-0.75}$·d^{-1} (range 79-154) or approximately 50 percent more than BMR, and the mean cost of running was 1.8 (range 1.3-2.3) kcal·kg BW$^{-0.75}$·km^{-1}. It is of note that humans also require

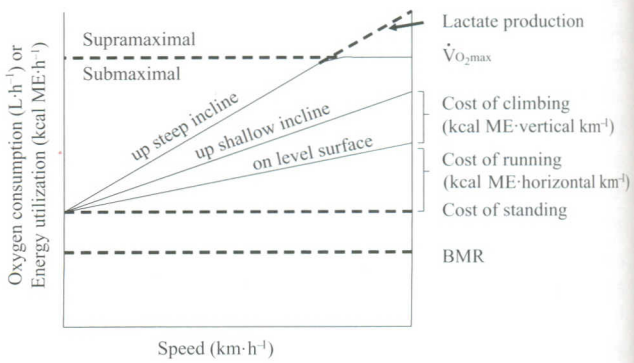

FIGURE 11-3 Cost of running on a treadmill.

TABLE 11-6 Cost of Standing and Running During Steady-State Exercise on a Treadmill for Dogs and Cats

Subjects	*n*	BW (kg)	Midpoint or Mean[a]	Standing (intercept) (kcal·kg $BW^{-1}·h^{-1}$)	Standing (intercept) (kcal·kg $BW^{-0.75}·d^{-1}$)	Running (slope of curve) (kcal·kg $BW^{-1}·km^{-1}$)	Running (slope of curve) (kcal·kg $BW^{-0.75}·km^{-1}$)	Speed ($km·h^{-1}$)	Reference
Mongrel dogs	1	2.6	2.6	3.6	110	1.6	2.1	1.5-10	Taylor et al., 1970
Dogs	2		4.4	4.1	144[b]	1.9	1.3[b]	2-20	Taylor et al., 1982
Male beagles	6	8.8-12.5	10.6	2.4	105[b]	1.0	1.7[b]	6	Young et al., 1959c
Male mongrel dogs	3	6.7-17.3	12.8	2.5	115	0.9	1.6	3-6	Raab et al., 1976
Mongrel dogs	1	18	18	3.1	154	0.8	1.7	1.5-10	Taylor et al., 1970
Dogs			21	1.5	79[b]	1.1	2.3[b]		Taylor et al., 1982
Female foxhounds	10	21.8 ± 1.4	21.8	4.7	243[b]	1.4	3.1[b]	4.8-6.4	Ordway et al., 1984
Mongrel dogs	5	19-29	24	1.9	99[b]	0.9	2.0[b]	4-16	Ordway et al., 1984
Wolf	2		23.1	2.2	118[b]	1.1	2.4[b]	2-18	Taylor et al., 1982
Domestic cats	2		3.9	0.7	28[c]	1.9	3.0[c]	0.5-5	Taylor et al., 1982

[a]A mean is reported where this is known; otherwise, the midpoint between maximum and minimum is reported.
[b]Values are approximate because they were calculated using the mean or midpoint value to the 0.75 power.
[c]Values are reported relative to kg $BW^{0.67}$ and are approximate because they were calculated using the mean to the 0.67 power.

approximately 1 kcal·kg $BW^{-1}·km^{-1}$ when running on a treadmill (Margaria et al., 1963), but a dog of similar weight to an average human (70 kg) would probably require only 60 percent of this amount.

Taylor et al. (1982) also measured the cost of running in two cats. The mean cost of standing was 28 kcal·kg $BW^{-0.67}·d^{-1}$ and the mean cost of running was 3 kcal·kg $BW^{-0.67}·km^{-1}$. These values were less than and similar to the interspecies mean, respectively.

Exercise Up- and Downhill

An animal gains potential energy (2.34 kcal·kg BW^{-1}·vertical km^{-1}) as it moves uphill. The efficiency of muscles in converting chemical to potential energy determines how much chemical energy is required to move uphill (Schmidt-Nielsen, 1984). Taylor et al. (1972) estimated the energy cost of gaining height by subtracting the energy cost per meter run on a horizontal treadmill from the energy cost per meter run on a sloping treadmill and dividing the difference by the height gained in meters for each meter run on the treadmill (percent slope of the treadmill). Using this method, Cohen et al. (1978) found that the energy required to gain height and muscular efficiency was constant (6.5 kcal·kg BW^{-1}·vertical km^{-1} and 36 percent, respectively), irrespective of body weight in mammals ranging from 0.25 to 253 kg BW.

Only a few studies (Table 11-7) have measured energy consumption on both horizontal and sloping treadmills, enabling the same method as that used by Taylor et al. (1972) and Cohen et al. (1978) to be used to estimate the efficiency of canine muscle. There is, however, a clear disparity between the first two and the second two studies listed in Table 11-7. The first two studies reported that the efficiency with which dogs gain height is similar to that reported by Cohen et al. (1978) for other mammals and that the efficiency declines slightly as the slope of the treadmill increases above 5-7 percent (Cerretelli et al., 1964; Raab et al., 1976). The average efficiencies were 37 percent on a 5-7 percent slope, 32 percent on a 10-12 percent slope, and 29 percent on a 20 percent slope (i.e., 6-8 kcal·kg BW^{-1}·vertical km^{-1}). The other two studies reported a much lower mean efficiency (17 percent), and the mean efficiency increased and then decreased slightly with slope (Young et al., 1959c; Ordway et al., 1984).

The first two studies measured energy consumption in fewer dogs but did so at two or more speeds, which increases the accuracy of the estimate of energy expenditure per kilometer. The latter two studies used more dogs, but measurements were made at only one speed, which increases the possibility of error when measuring the cost of running. Furthermore, it seems unlikely that the efficiency of dog muscle should be any lower than that of other mammals. Zuntz (1903), however, showed that the efficiency of a dog climbing a slope improved with practice. Until more studies have been performed therefore, the higher estimates from the first pair of studies listed in the table are assumed to be the better estimates.

It is also assumed that the efficiency of canine muscle does not change with body weight. The relationship in dogs between body weight and efficiency cannot be determined from the studies listed below because all studies used dogs of similar body weight. Theoretical considerations, however, suggest that muscular efficiency should prove unrelated to body weight (Schmidt-Nielsen, 1984), in which case the energy to gain altitude will be directly proportional to body weight, whereas horizontal running is proportional to

TABLE 11-7 Efficiency of Gaining and Losing Height When Running

Subjects	*n*	Speed ($km \cdot h^{-1}$)	BW (kg)	Slope (%)	Energy Utilization ($kcal \cdot kg\ BW^{-1} \cdot km^{-1}$ along treadmill)	Energy Utilization ($kcal \cdot kg\ BW^{-1} \cdot km^{-1}$ gained vertically)	Efficiency (%)	Reference
Male mongrel dogs	3	3-6	7-17	20	2.4	7.5	31	Raab et al., 1976
				12	1.6	6.7	35	
				7	1.3	5.5	42	
				0	0.85	—	—	
				–7	0.7	2.6[a]	111[a]	
				–12	0.6	2.3[a]	97[a]	
				–20	0.6	1.4[a]	59[a]	
2-4-year-old mongrel dogs	5	4-16	19-29	20	2.5	8.2	28	Cerretelli et al., 1964
				10	1.7	7.8	30	
				5	1.2	6.7	35	
				0	0.9	—	—	
1-1.5-year-old female foxhounds	10	6	22 ± 1	20	4.2	14	17	Ordway et al., 1984
				16	3.6	13	17	
				12	3.1	14	17	
				8	2.3	11	21	
				4	2.2	19	12	
				0	1.4	—	—	
11-month-old male beagles	5	6	9-12	37	6.5	14.7	16	Young et al., 1959c
				33	4.9	12.2	19	
				28	4.4	12.4	19	
				21	3.6	12.6	18	
				14	2.5	10.7	22	
				7	2.2	18.1	13	
				0	1.0	—	—	

[a]Values represent potential energy saved compared to running on the level.

$BW^{0.67}$. A small 4-kg cat or dog would, therefore, need to increase its energy consumption much less when climbing than would a large 40-kg dog. The study by Raab et al. (1976) also found that dogs recover the potential energy that they are losing when running down a slope of less than 11 percent but recover only 59 percent of the lost potential energy when running down a 20 percent slope, probably because work has to be done to prevent falling at steeper gradients (Blaxter, 1989).

There appear to be no studies measuring the efficiency of cats moving up- and downhill at present. It must be assumed, therefore, that the efficiency of feline muscle is similar to that of muscle in other species.

Several studies have measured energy consumption in dogs running on sloping treadmills but have not reported either the energy required for standing or the efficiency with which the dogs were able to gain height. It is not possible, therefore, to estimate the energy required for running unless some assumptions are made. Slowtzoff (1903), for example, measured the energy consumption of running dogs of body weights varying from 5 to 37 kg, but varied the slope of the treadmill among dogs and did not measure the cost of level running. If it is assumed, based on the previous discussion, that the cost of standing was 137 $kcal \cdot kg\ BW^{-0.67} \cdot d^{-1}$ and the efficiency of climbing was 37 percent for a 5-7 percent slope, it is possible to regress the estimated energy required for running against body weight. This gives a cost of level running (3.1 $kcal \cdot kg\ BW^{-0.72} \cdot km^{-1}$) similar to that of Ordway et al. (1984) but much higher than other estimates. Marconi et al. (1982) also reported data that suggest a high cost of running (1.9 $kcal \cdot kg\ BW^{-1} \cdot km^{-1}$ for 15-17-kg BW dogs). Issekutz (1979), however, reported that dogs required only 2 ± 0.07 $kcal \cdot kg\ BW^{-1} \cdot km^{-1}$ when running at 100 $m \cdot min^{-1}$ on a 15 percent slope, which is equivalent to 1.1 $kcal \cdot kg^{-1} \cdot km^{-1}$ in level running if a 32 percent efficiency of climbing is assumed.

Rough Terrain

The energy cost of running over rough terrain is much greater than that of running on a smooth surface, such as a treadmill. Reindeer, for example, used 13 and 38 percent more energy, respectively, when walking on dry and wet tundra compared to walking on hard-packed roads (White

and Yousef, 1977). The energy cost of walking in snow is even higher and increases exponentially as the sinking depth approaches chest height. The energy requirement for walking increased two to three times when wild ungulates sank 50 percent of brisket height into snow and five- to sevenfold when they sank 80 percent of the height of the brisket (Fancy and White, 1985). These increases are probably similar for dogs and cats, though dogs and cats tend to hop rather than walk through deep snow. Energy requirements are also likely to be greater in a lead dog than in following dogs.

Load Carrying

Energy consumption in dogs and other animals appears to increase in direct proportion to the mass of the load carried, irrespective of the size or speed of the animal, but with slight variation dependent on the disposition of the load (i.e., if the load increases by 10 percent of body mass, energy consumption increases by 10 percent). Because small animals have a higher cost for locomotion than large animals, the increase in energy to carry a given load is greater in small than in large animals (Schmidt-Nielsen, 1984).

Pulling Weights

Work done by traction in pulling a load is the product of tractive force (measured with a dynamometer) times distance. Taylor (1957) measured the tractive work of nine sled dogs pulling a sled in the Antarctic. These dogs were 1-6 years of age, "slow and strong," and heavier (33-46 kg BW with a mean of 39 kg BW) than most racing sled dogs. Dogs had three gaits. With very light loads (0-88 newtons), dogs galloped at 11-25 $km \cdot h^{-1}$, the highest speeds being achieved when going downhill with the towing rope slack. With intermediate loads (88-539 newtons), dogs trotted at 8-11 $km \cdot h^{-1}$, and with heavy loads (539-1,323 newtons) reached a maximum of 1,100 $kcal \cdot h^{-1}$ (7-8 $kcal \cdot kg\ BW^{-0.75} \cdot h^{-1}$), whether dogs were trotting or walking. This value probably represents maximal aerobic exercise. A higher rate of work (1,350 $kcal \cdot h^{-1}$) was possible over shorter distances (706-newton load at 8 $km \cdot h^{-1}$ for 9 minutes). The heaviest load was 1,156 newtons at 3 $km \cdot h^{-1}$ for 4 minutes. These higher rates of work were probably supramaximal because they could not be maintained for long. Maximal work occurred at one-third the top speed and one-third the greatest pull when trotting, and at two-thirds the load and one-sixth the speed for walking.

The energy cost of tractive work is the difference between walking or running with or without load. Efficiency is the ratio of the work done and the energy cost. The efficiency of dogs appears not to have been measured, but the efficiency of draught horses and humans is approximately 33 percent (Blaxter, 1989). The energy cost of pulling the sled was therefore probably three times the tractive force measured by Taylor and would have been additional to the cost of running, the cost of standing, and the cost of maintaining body temperature.

Wind Resistance and Swimming

When moving through air or water, the rate of energy consumption (power) necessary to overcome wind resistance or drag is proportional to the force required to combat drag multiplied by the speed. The force to overcome drag increases in proportion to the square of the velocity and the maximal cross-sectional area in the direction of motion (the breadth of the chest in dogs and cats). Energy consumption, therefore, increases exponentially with (the cube of) speed (Blaxter, 1989).

Dogs on treadmills do not have to overcome wind resistance, but wind resistance may be an important extra load for dogs and cats running across terrain. In humans, experiments suggest that the energy required to overcome wind resistance is approximately 8 percent of the total in distance runners running at 5 $m \cdot s^{-1}$, 15 percent of the total in sprinters running at 10 $m \cdot s^{-1}$, and the energy required to run into a wind of 18 $m \cdot s^{-1}$ would be 70 percent more than if there were no wind (Blaxter, 1989). There appear to be no similar studies in dogs and cats, but quadrupeds present a smaller cross-sectional area to the air than do humans; so the increase in energy required to overcome wind resistance is probably less in dogs and cats than humans. The cost of running into a wind probably increases exponentially, however, with the speed of the wind, and it is likely that the lead dog in a team of dogs will require more energy than dogs running behind it, especially in a head wind. Similarly, the energy required for swimming has not been determined in dogs, but the energy cost of swimming is likely to be high, to increase rapidly with increasing speed, and to be greater in dogs with broad rather than narrow chests.

Other Activities

Drinking, grooming, stretching, playing, and jumping all increase heat production, and the energy required to support them has not been measured in dogs or cats.

Maximal Oxygen Consumption

Heat production and oxygen consumption increase with exercise until oxygen consumption reaches a maximum ($\dot{V}O_2max$) (Seeherman et al., 1981). Work above $\dot{V}O_2max$ (termed supramaximal) is possible only using energy from anaerobic glycolysis and results in the rapid accumulation of lactic acid. Supramaximal exercise rapidly results in exhaustion, whereas submaximal exercise can continue for long periods and indefinitely when fat is the source of energy. Taylor et al. (1981) reported that regression gave $\dot{V}O_2max$ as 6.9 $L\ O_2 \cdot h^{-1} \cdot kg\ BW^{-0.81}$ among 22 species of

mammal. This is equivalent to 796 kcal·kg $BW^{-0.81}$·d^{-1}, which is approximately 10 times Kleiber's estimate for resting oxygen consumption between species (Kleiber, 1932).

It is not easy to persuade dogs to exceed their $\dot{V}O_2max$ (Donald and Ferguson, 1966). The maximal speed of most treadmills has proved too slow to measure $\dot{V}O_2max$ in dogs running on the level, and most measurements have been obtained with dogs running up a slope. Weibel et al. (1983) reported having to reduce the ambient temperature to 5°C to prevent rectal temperatures from rising too high when dogs and wild canids were running faster than $\dot{V}O_2max$. As a result, oxygen consumption in some studies did not reach a plateau, and $\dot{V}O_2max$ must be higher than the highest value obtained. Training can also affect $\dot{V}O_2max$ (Musch et al., 1985), and the intensity of training almost certainly varied among studies. Many authors state that dogs were "trained to run on the treadmill," but this would have resulted in only slight conditioning compared to dogs that ran many kilometers daily. Only a few authors describe withholding exercise prior to a study.

It is not surprising, therefore, that $\dot{V}O_2max$ in adult dogs has varied from 5.6 to 10.6 L O_2·kg BW^{-1}·h^{-1}, which is equivalent to 50-106 kcal·$kg^{-0.75}$· h^{-1} (Table 11-8). The $\dot{V}O_2max$ was 56 percent lower in 5-month-old beagles and 30 percent lower in 6-8-month-old beagles than in 11-month-old beagles (Young et al., 1959c). The $\dot{V}O_2max$ was 31 percent lower in 10- to 14-year-old female beagles than in 2- to 3-year-old male beagles (Haidet, 1989), and $\dot{V}O_2max$ increased 28 percent with training in 1- to 2-year-old foxhounds (Musch et al., 1985). The $\dot{V}O_2max$ decreased in old dogs and increased with training in parallel with changes in cardiac output and smaller changes in arteriovenous oxygen difference. Old age and training did not affect oxygen consumption at rest or at each level of activity; only the tolerance for the highest level of activity was affected. Reynolds et al. (1999) found that $\dot{V}O_2max$ declined with training in dogs fed a 19 percent ME protein diet but was unaffected by training in adult sled dogs fed a diet containing 24 percent ME protein or more. The $\dot{V}O_2max$ in these sled dogs was very much higher than reported by Musch et al. (1985), but training was slightly less intense and the duration of exercise each day was half as long. The $\dot{V}O_2max$ was also lower when dogs were exercised in a low-oxygen environment: $\dot{V}O_2max$ (FiO_2 0.15) was <75 percent of $\dot{V}O_2max$

TABLE 11-8 Maximal Oxygen Consumption in Dogs

						Conditions		$\dot{V}O_2max$		
Subjects	Age	Gender	Training	*n*	BW (kg)	Speed ($km·h^{-1}$)	Slope (%)	(L O_2·kg^{-1}·h^{-1})	(kcal·$kg^{-0.75}$·h^{-1})	Reference
Beagles	10-14 yrs	F	N	7	10 ± 1	6	23	4.8 ± 1.2	42 ± 10[a]	Haidet, 1989
	2-3 yrs	M	N	7	10 ± 1	7	30	7.1 ± 0.6	61 ± 5[a]	
Beagles	11 mos.	M	Y	5	9-12	6	37	8.1	70[a]	Young et al., 1959c
	5 mos.							3.6		
Mongrels	Adult	MF	Y	8	9-13	8-13	8-20	5.8 ± 0.5	50 ± 4[a]	Lucas et al., 1980
Dogs			Y	8	10-14	5	28	>5.1± 1.2[b]	>46 ± 11	Donald and Ferguson, 1966
Mongrels			Y	4	15-17	>8	10	5.6	54[a]	Marconi et al., 1982
Dogs	Adult	M	Y	5	17-20	13	18	>3.7 ± 0.7[b]	>37 ± 8	Bailie et al., 1961
Alaskan sled dogs										Reynolds et al., 1999
>24% ME as protein diet			N	2	20 ± 3			10.3 ± 4.6	105 ± 46[a]	
			Y	4	19 ± 2			10.6 ± 4.1	106 ± 41[a]	
19% ME as protein diet			N		20 ± 3	>5	>5	9.5 ± 4.4	97 ± 45[a]	
			Y	8	19 ± 2			7.8 ± 2.2	78 ± 22[a]	
Mongrels	3-4 yrs	M	Y	4	18-25	0-16	10			Piiper et al., 1966
21% O_2								>6.0[b]	>62[a]	
15% O_2								4.5	47[a]	
11% O_2								3.0	31[a]	
Foxhounds	1-1.5 yrs	F	N	7	22 ± 1	>6.4	20-24	6.7 ± 1.2	70 ± 12[a]	Ordway et al., 1984
Foxhounds	1-2 yrs	F	N	10	22 ± 1	>6.4	20-24	6.8 ± 0.7	71 ± 7	Musch et al., 1985
			Y		22 ± 1			8.8 ± 0.6	92 ± 7	
Mongrels		M	Y	8	20-27	12	20	8.1 ± 0.5	89 ± 6[a]	Wagner et al., 1977
						16	16			
Mongrels	2-4 yrs		Y	5	19-29	16	10	>6[b]	>66[a]	Cerretelli et al., 1964
						10	20			
Foxhounds	2-4 yrs	M	Y	10	25 ± 2	10-13	0-25	7.8 ± 0.7	84 ± 7[a]	Wu et al., 2001
Dogs			Y	2	19, 32	36	24	10.2, 9.0	102, 103	Weibel et al., 1983

[a]Values are approximate since they were calculated using the mean or midpoint value to the 0.75 power.
[b]The $\dot{V}O_2max$ must be higher than the highest value measured because oxygen consumption did not reach a plateau.

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(Fio_2 0.21), and $\dot{V}o_2max$ (Fio_2 0.11) was <50 percent of $\dot{V}o_2max$ (Fio_2 0.21) (Piiper et al., 1966).

The $\dot{V}o_2max$ is much higher in trained adult dogs in a normal environment (15-30 times BMR) than in most other species, but similar to $\dot{V}o_2max$ in wild canids (Weibel et al., 1983). Weibel et al. (1983) reported that $\dot{V}o_2max$ in dogs was similar to that of foxes, coyotes, and wolves, and regression suggested that $\dot{V}o_2max$ varied with BW to the 0.9 power (i.e., it was 63 $kcal \cdot kg^{-0.9} \cdot h^{-1}$ among domestic and wild canids). Regression of $\dot{V}o_2max$ for trained adult dogs reported in Table 11-8 suggests that $\dot{V}o_2max$ increases with body weight to the 1.2 power (i.e., $\dot{V}o_2max$ is 62 $kcal \cdot kg^{-1.2} \cdot h^{-1}$ for dogs).

The $\dot{V}o_2max$ of domestic cats appears not to have been measured, but oxygen consumption did not reach a plateau in two cats running at almost 5 $km \cdot h^{-1}$ on a treadmill (Taylor et al., 1982). At their greatest speed, these 3.9-kg cats were consuming 2.2 L $O_2 \cdot kg^{-1} \cdot h^{-1}$, which is equivalent to 16 $kcal \cdot kg^{-0.67} \cdot h^{-1}$ or 391 kcal·kg $BW^{-0.67}$ daily, (i.e., approximately five times BMR). This may be close to the $\dot{V}o_2max$ of cats. The $\dot{V}o_2max$ of the gastrocnemius was five times higher in dogs than cats (Cerretelli et al., 1969). Since dogs have a $\dot{V}o_2max$ that is up to 30 times BMR, cats probably have a $\dot{V}o_2max$ that is no more than 6 times BMR.

Intensity of Exercise

The strenuousness of a bout of exercise is often classified in terms of oxygen consumption either as multiples of oxygen consumption at rest ($\dot{V}o_2rest$) or as a percentage of $\dot{V}o_2max$. In humans, exercise has been classified as light if oxygen consumption is less than three times $\dot{V}o_2rest$; moderate if more than three and less than six times $\dot{V}o_2rest$; heavy if more than six times $\dot{V}o_2rest$, and maximal if ten times $\dot{V}o_2rest$ (McArdle et al., 1996). For dogs, most studies report the severity of exercise as a percentage of $\dot{V}o_2max$. Thus, the severity of exercise could be considered light if less than 30 percent of $\dot{V}o_2max$; moderate if 30-60 percent of $\dot{V}o_2max$; heavy if 60-100 percent of $\dot{V}o_2max$; and very heavy if supramaximal. In cats, a similar classification scheme to that in dogs is not possible because $\dot{V}o_2max$ has not been determined. Nevertheless, the fastest that a cat has been induced to run is approximately five times $\dot{V}o_2rest$, which suggests that light exercise would be up to twice $\dot{V}o_2rest$, moderate would be 2-3 times $\dot{V}o_2rest$, and heavy would be more than three times $\dot{V}o_2rest$.

Burger (1994) categorized activity in dogs as low if dogs exercised for less than 1 hour, moderate if they exercised for 1-3 hours, and high if they exercised for 3-6 hours. When considering energy and nutrient requirements, the distance traveled is more important than the intensity or duration of exercise. Thus, exercise would be very low when dogs are confined to cages, low when dogs are confined to pens or runs or exercise for less then 2 km daily, moderate when dogs run between 2 and 20 km daily, heavy when dogs run more than 20 km daily, and very heavy when dogs run more than 80 km daily.

Field Metabolic Rate

Several studies have measured the daily energy requirements of free-living animals either by measuring food intake or by measuring metabolic rate using the doubly labeled water method (Table 11-9). Doubly labeled water consistently gives higher values than food intake studies. Estimates of ME that have used modified Atwater factors (NRC, 1985), however, may have underestimated the digestibility, and therefore the ME density, of many foods fed to dogs and cats. This is not the case for studies such as those by Hill et al. (2000, 2001b), which measured digestibility directly. Studies that have relied on food surveys may also give artificially low estimates of ME because underreporting of food consumption is common.

In many studies, the effect of exercise is also complicated by the effect of ambient temperature. Kuhn and Hardegg (1988), for example, found that foxhounds kept outside in 72-m^2 enclosures exposed to ambient temperatures of 7-30°C ate 17 percent more than foxhounds kept indoors in 16-m^2 pens in an ambient temperature of 18-22°C. The average MER of sled dogs in kennels in a thermoneutral environment has been reported to be approximately 125 $kcal \cdot kg^{-0.75} \cdot d^{-1}$ (Durrer and Hannon, 1962; Finke, 1991) but increased in the cold to more than 320 $kcal \cdot kg^{-0.75} \cdot d^{-1}$ in sedentary dogs at –30°C when there was a wind chill (Durrer and Hannon, 1962; Campbell and Donaldson, 1981; Hinchcliff and Reinhart, 1996). Kronfeld (1973) reported anecdotally that the requirements of sled dogs double during exercise and triple if exercise is performed in a cold environment.

Sled dogs exercising in the cold use the most energy. Hinchcliff et al. (1997b) reported that mean energy consumption of sled dogs competing in a long-distance race in ambient temperatures well below freezing was a remarkable 11,260 kcal or 1,050 $kcal \cdot kg^{-0.75}$ daily. This was four times greater than trained but sedentary dogs kept at a similar ambient temperature. Over the 70 hours of the 490-km race, this represents 2.3 $kcal \cdot km^{-1}$ or 4.7 $kcal \cdot km^{-1} \cdot kg\ BW^{-0.75}$ (i.e., only 2.5 times the energy required for running on a level treadmill without a sled to pull). Wyatt (1963) reported that sled dogs consuming up to 2,400 kcal ME daily were barely able to maintain body weight when tethered and lost weight rapidly when working. The body weight of dogs is not stated, but the average weight of sled dogs in the Antarctic when this study was performed was approximately 40 kg (Raab et al., 1976), which suggests that sled dogs in this environment needed more than 150 kcal ME·kg $BW^{-0.75}$ daily. Orr (1966) found that after an initial drop in body weight, tethered dogs maintained weight when consuming 145 kcal ME·kg $BW^{-0.75}$ daily, and dogs pulling a heavy load across ice 32 $km \cdot d^{-1}$ maintained weight when consuming 270 kcal

TABLE 11-9 Field Metabolic Rate in Dogs

Animals	Gender	Training	*n*	BW (kg)	Age (yr)	Temperature (°C)	Nature of Exercise	Method	Daily Energy Consumption (kcal)	Daily Energy Consumption ($kcal \cdot kg^{-0.75}$)	Reference
Alaskan sled dogs	MF	Y	18	23 ± 6	1-4	–10 to –35	Race for 490 km over 70 h at 7 $km \cdot h^{-1}$	DLW	11,260 ± 2,820	1,052 ± 192	Hinchcliff et al., 1997b
								ME[a]	10,660	980	
		Y	4			–10 to –35	Sedentary in kennels	DLW	2,510 ± 1,625	263 ± 96	
		N	6			20	Sedentary in kennels	ME[a]		130 ± 29	
Alaskan huskies		Y	13	19			634 km over 8 d	DLW	4,014 ± 3,084	438[b]	Decombaz et al., 1995
								ME	2,089 ± 438	228[b]	
Sled dogs	M	Y	8	39-43	0.7-9	–8	32 $km \cdot d^{-1}$ pulling heavy load over ice	ME	4,368	270 ± 17	Orr, 1966
			7	35-38		Antarctic	Tethered to 2-m chains		2,184	145 ± 7	
Cross-bred Alaskan huskies		Y		20-25		–12 to 2	10 $km \cdot d^{-1}$		4,000-5,000	440	Kronfeld et al., 1977
						–4 to 7	6 $km \cdot d^{-1}$		2,000-2,500	220	
Kelpie	M	Y	1	17			Sheepdog worked for 2 afternoons of 8 d, 40-min run daily and short walks	DLW	1,426	167	Frankel and Bell, 1994
								ME[a]	1,257	147	
Border collies[c]			10				High: 3-6 h	ME[a]		174 ± 179	Burger, 1994
			28				Moderate: 1-3 h			124 ± 89	
			9				Low: <1 h			97 ± 82	
Border collies[c]	MF	Y	31	17 ± 6	1-12		Kennels; 15 min to 3 h work daily on fell and valley sheep farm	ME[a]	1,640-2,190	138-184[b]	Downs et al., 1997b

Border collies[c]								ME[a]			Butterwick and Hawthorne, 1998
Pets			7				3-6 h·d^{-1}			177 ± 132	
			28				1-3 h·d^{-1}			108 ± 51	
			5				<1 h·d^{-1}			120 ± 59	
Working			11				3-6 h·d^{-1}			174 ± 118	
			10				1-3 h·d^{-1}			184 ± 40	
			7				<1 h·d^{-1}			143 ± 64	
English pointers	MF	Y	10	20 ± 1	1-11	Hot and humid	11-m^2 run; 3 h hunting daily	ME	2,300 (1,900-2,600)	240[b] (200-280)	Davenport et al., 2001
Labrador retrievers	F	Y	6	23-30	5-11		Heated kennels with outside runs; 10- min walk daily but gained 2 kg BW	ME	1,120-1,440	93-121[b]	Downs et al., 1997a
Greyhounds	MF	Y	7	34 ± 4	1-3	11 to 25	3-m^2 kennels; 900-m^2 paddock for 30 min daily; 500-m race twice weekly	ME	2,160 ± 330	155±18	Hill et al., 2000
Greyhounds	MF	Y	8	32 ± 6	2-4	–4 to 15	As above	ME	2,070 ± 720	152 ± 46	Hill et al., 2001b
Greyhounds	MF	Y	9		2-5		As above	ME			Hill et al., 1999b
• Free-choice				30 ± 7						155 ± 34	
• Restricted				28 ± 6						137 ± 22	
Beagles	F	Y	10	12.3	1.3		200 km per week on 15% slope	Energy	1,530 ± 600	233 ± 92[b]	Arokoski et al., 1993
		N	10				1-m^2 cage only		1,030 ± 450	156 ± 69[b]	
Beagles	F		2	17,11	8		3-m^2 kennels with outside runs	DLW	874	122	Ballevre et al., 1994
								ME[a]	784	109	

NOTE: DLW double labeled water method; energy is energy equivalent, but type of energy is not stated.

[a]ME was calculated using recommendations of the NRC (1985) and would be approximately 4 percent higher if calculated with the recommendations in this report.

[b]Approximate estimates obtained using published mean body weight.

[c]Whether there is some overlap in the dogs and data used in these studies is unclear.

ME·kg $BW^{-0.75}$ daily. Kronfeld et al. (1977), however, reported that cross-bred Alaskan huskies at ambient temperatures close to freezing consumed approximately 220 kcal·$kg^{-0.75}$·d^{-1} when running 3-7 km daily and approximately 440 kcal·$kg^{-0.75}$·d^{-1} when running 8-9 km daily. Reynolds et al. (1999), by contrast, found that mean daily energy consumption (139 kcal·$kg^{-0.75}$) did not increase when sedentary dogs started to run 40-60 km weekly. These authors noted, however, that exercise events were intense but short in duration, that ambient temperature was higher during training, and that dogs subjectively appeared to sleep more during the day when in training and were more active when confined to their chains.

Hunting and herding dogs require intermediate amounts of energy (Table 11-10). Davenport et al. (2001) reported that 20-kg English pointers maintained or slightly gained weight during the hunting season when consuming 114 kcal ME·kg BW^{-1} daily (approximately 240 kcal ME·$kg^{-0.75}$·d^{-1}). Herding dogs appear to require on average 184 kcal ME·$kg^{-0.75}$·d^{-1} (Burger, 1994; Frankel and Bell, 1994; Downs et al., 1997b; Butterwick and Hawthorne, 1998). Racing greyhounds, however, race over relatively short distances (<1 mile) usually no more than twice weekly. It is not surprising, therefore, that these dogs consume little more ME than a moderately active dog. Kohnke (1989) reported that Australian greyhound trainers fed a mean of 2,400 kcal daily to female and 2,600 kcal daily to male greyhounds. This would be the equivalent of 214 kcal·kg $BW^{-0.75}$ daily for a 25-kg female or a 28-kg male dog. Hill et al. (1999b, 2000, 2001b), however, found that racing greyhounds in training fed free-choice but time-limited meals of dry dog food once daily maintained body weight while consuming 155 kcal ME·kg $BW^{-0.75}$ daily. Greyhounds ran 0.7 km·h^{-1} faster, however, when ME intake was slightly restricted to 137 kcal·$kg^{-0.75}$ daily (Hill et al., 1999b).

TABLE 11-10 Recommendations for Metabolizable Energy Requirements of Exercising Dogs

	ME Requirement	
Condition	Mean	Range
BMR (kcal·kg $BW^{-0.75}$·d^{-1})[a]	76	48-114
RFMR (kcal·kg $BW^{-0.75}$·d^{-1})[a]	84	51-127
Standing (kcal·kg $BW^{-0.75}$·h^{-1})[b]	4.6	3.3-6.4
Running (kcal·kg $BW^{-0.75}$·horizontal km^{-1})[b]	1.8	1.3-2.3
Climbing (kcal·kg BW^{-1}·vertical km^{-1})[b]	7	6-8
Racing sled dogs 168 km·d^{-1} in extreme cold (kcal·kg $BW^{-0.75}$·d^{-1})	1,050	860-1,240
Sled dogs pulling heavy loads 32 km·d^{-1} (kcal·kg $BW^{-0.75}$·d^{-1})	270	250-290
Hunting dogs (kcal·kg $BW^{-0.75}$·d^{-1})	240	200-280
Working Collies (kcal·kg $BW^{-0.75}$·d^{-1})	184	80-380
Racing greyhounds (kcal·kg $BW^{-0.75}$·d^{-1})	140	120-160
Increase for each °C ambient temperature below or above thermoneutral zone (kcal·kg $BW^{-0.75}$·d^{-1})	3	2-5

[a]From Chapter 3.

[b]To estimate the requirement for running on a smooth surface, add the cost of running and the cost of climbing to the cost of standing for the duration of the run.

Pet dogs and dogs in cages or kennels require the least energy, but energy requirements vary considerably between studies and between individuals depending on the level of activity and ambient temperature. Individual values vary from less than 100 to more than 200 kcal·kg $BW^{-0.75}$·d^{-1} (Arokoski et al., 1993; Ballevre et al., 1994; Butterwick and Hawthorne, 1998; Connor et al., 2001; Patil and Bisby, 2002). It is impossible, therefore, to make a specific recommendation for any particular animal. Each animal should be treated as an individual and food adjusted to its environmental situation and activity. Food intake should be adjusted, therefore, to maintain optimal body condition.

NUTRIENT REQUIREMENTS

How May Nutrient Requirements Change with Exercise or in the Cold?

Diets for any life stage or condition are balanced for animals undertaking average amounts of activity in a nonstressful thermoneutral environment (i.e., they provide adequate but not excess nutrients when animals are fed enough food to maintain body weight and condition). Since most studies examining nutrient requirements have been performed on dogs and cats in kennels, most diets are balanced for dogs and cats undertaking the same amount of activity as those in kennels. This activity may be more than that performed by some pet animals but is much less than that undertaken by some working dogs.

Exercise and keeping warm in the cold both require energy. If the energy density of the diet does not change, dogs and cats have to increase food intake to maintain energy balance in the cold or as activity increases. Intake of all nutrients will then increase or decrease in proportion to the amount of food eaten and the amount of activity. Nutrient requirements may not, however, parallel changes in energy intake. As exercise decreases, the absolute amount of a nutrient required by an animal may decrease proportionately with energy intake, may decrease less than energy intake, or may remain the same despite decreased energy intake. In the latter case, it is quite possible that animals, such as some pets, consuming less food because they are undertaking less activity than the average laboratory animal, could consume inadequate amounts of an essential nutrient if the diet has been balanced by assuming an average amount of activity. To ensure adequate intake of essential nutrients, therefore, a dog undertaking little activity and consuming little more than the RFMR may have to consume a diet that is up to twice as nutrient dense as a diet fed to a dog or cat undertaking average amounts of exercise and requiring up to twice as much energy. In practice, the lower limits expressed relative to DM or ME should be increased by 1.5 times for

diets intended for sedentary animals but expressed relative to body weight will remain the same unless lack of exercise has been shown to modify the requirement.

In a similar fashion, as exercise increases, the absolute requirement for a nutrient may increase at the same rate, may increase faster or slower than the requirement for energy, may increase slightly and then stop increasing, or may remain unchanged irrespective of the amount of activity. In the latter case, animals undertaking heavy exercise and consuming large amounts of food balanced for a dog undertaking average amounts of exercise could take in excessive amounts of some potentially toxic substance such as a trace mineral. In practical terms, safe upper limits (SULs) expressed relative to DM and ME should be decreased eightfold in diets intended for sled dogs running in a cold environment and halved in diets for working dogs. Safe upper limits expressed relative to body weight will remain the same unless increased exercise has been shown to modify the requirement.

Requirements may also vary with the amount of another nutrient in the diet (e.g., vitamin E requirements with fat), the type of exercise (endurance vs. sprinting), the amount of training, the breed, or the gender of the animal. Therefore, an animal undertaking endurance exercise may not take in enough of an essential nutrient, such as fat or vitamin E when fed a diet formulated for an animal undertaking average activity. The same also applies for various environmental conditions. There is, thus, a complex matrix of nutrient requirements and energy intakes for each level of activity, amount of training, and ambient temperature and for each life stage, breed, or gender. This chapter primarily considers how requirements for adult maintenance change as activity and environment change. There is little information however for many points in the matrix, and it is recommended where there is some uncertainty to (1) reduce nutrient density relative to DM and ME of potentially toxic nutrients, as described above, in diets designed for dogs that require more energy such as dogs that live in a cold environment or working dogs; and (2) increase the nutrient density relative to DM and ME of essential nutrients in diets fed to sedentary animals living in a thermoneutral environment.

Sources of Energy: Fat Versus Carbohydrate

The energy for muscle contraction comes from four chemical sources: ATP, creatine phosphate, anaerobic metabolism of carbohydrate, or aerobic metabolism of amino acids, glucose, and fat. Energy for muscular contraction is obtained directly from the high-energy phosphate bonds of ATP. One molecule of ATP may then be regenerated from ADP (adenosine diphosphate) at the expense of the high-energy phosphate bond in creatine phosphate. High-energy phosphate bonds are continually replenished either anaerobically by glycogenolysis and glycolysis or aerobically from fat or glucose by oxidation.

The muscle fibers in dogs and cats differ in the degree to which they rely on either aerobic or anaerobic sources of energy. Muscle fibers with low myosin adenosine triphosphatase (ATPase) activity contract slowly (slow twitch or type I), and those with high myosin ATPase activity contract more rapidly (fast twitch or type II) (Gunn, 1978a). In cats, type II muscle fibers can be differentiated further into type IIa fibers with a high capacity for aerobic metabolism, which are fatigue resistant, and type IIb fibers with low aerobic capacity that rely primarily on anaerobic metabolism and are easily fatigable (Maxwell et al., 1977). In dogs, all muscle fibers have a high aerobic capacity, are fatigue resistant, and contain high concentrations of the aerobic enzymes succinate dehydrogenase (SDH) and nicotinamide-adenine dinucleotide (NAD) tetrazolium reductase (Gunn, 1978a; Maxwell et al., 1980; Armstrong et al., 1982); there are no type IIb fibers. Cats have almost equal numbers of type I, IIa, and IIb fibers and have a third or less SDH in their muscle (Cerretelli et al., 1969; Maxwell et al., 1980). The $\dot{V}O_2max$ and blood flow at $\dot{V}O_2max$ in the gastrocnemius were five times higher in dogs than cats (Cerretelli et al., 1969). Thus, dogs are adapted for endurance exercise and using fat as an energy source, whereas cats are adapted for short bursts of activity such as that required when jumping and pouncing on small prey, using glycogen as the energy source.

Muscle fibers in dogs also appear to have a high anaerobic capacity because all but a few type I fibers contain high concentrations of the anaerobic enzyme glycogen phosphorylase (GP) (Gunn, 1978a). Guy and Snow (1981) found some type II fibers with lower SDH activity, but SDH activity was still greater in these fibers in dogs than in horses. Canine type II fibers also contain more glycogen at rest and rely more on glycogen as a fuel (Reynolds et al., 1997). Thus, all canine muscle fibers appear to have both high aerobic and high anaerobic capacity, but type I slow-twitch fibers tend to rely more on aerobic metabolism, while type II fast-twitch fibers tend to rely more on anaerobic metabolism (Gunn, 1978a; Reynolds et al., 1997). In dogs, the antigravity deep part of limb muscles and deeper muscles of the extensor groups of muscles in arm and thigh contain more slow-twitch fibers than the superficial muscles, and greyhound muscles contain more fast-twitch fibers (80-100 percent) than muscles in other breeds (20-100 percent) (Gunn, 1978a; Guy and Snow, 1981; Armstrong et al., 1982). A greater proportion of fast-twitch fibers (one-half vs. one-third) have also been found in sled dogs trained for "sprint" racing than in dogs trained for endurance racing (Reynolds et al., 1995, 1997). The relative proportions of muscle fiber types were not affected by training, however, in greyhounds and foxhounds (Gunn, 1978a; Parsons et al., 1985). The activities of both aerobic and anaerobic muscle enzymes (aldolase and citrate synthase, respectively) were increased in greyhounds compared to other breeds, but the activities of many enzymes (creatine kinase, lactate dehydrogenase) were

the same as in other breeds (Guy and Snow, 1981). All dogs, therefore, are adapted for endurance exercise and using fat as an energy source, but anaerobic sources of energy are probably more important in dogs trained for sprinting.

In humans, the maximal rate of energy expenditure varies for each source of energy, but the amount of each source limits the length of time that this maximal rate of expenditure can be maintained (Hultman et al., 1994). Only creatine phosphate and ATP are able to sustain speeds attained during a 100-m sprint, but muscle stores of creatine phosphate and ATP are so small that a high rate of energy expenditure can be maintained only for a few seconds. Carbohydrate oxidation supports the intermediate speed of marathon runners for 20 miles until all glycogen stores have been depleted, whereupon fat oxidation becomes the only source of available energy. Runners are then unable to accelerate (i.e., they "hit the wall"). Stamina is, therefore, limited by the amount of glycogen in muscle.

Dogs also sustain $\dot{V}O_2max$ for only short periods (approximately 5-10 minutes), but beagles were able to run for 2-3 hours at >75 percent of $\dot{V}O_2max$ on a slope of 26 percent at 6 $km \cdot h^{-1}$ (Young et al., 1959c). Brzezinska et al. (1980) reviewed studies of 242 mongrel dogs weighing 15-25 kg and reported that they were able to run for a mean of 3 hours (range 1.1-5.2 hours) on a 21 percent slope at 4-6 $km \cdot h^{-1}$, but found no correlation between time to exhaustion and resting muscle glycogen concentrations. There was, however, a negative correlation between time to exhaustion and body weight.

Issekutz (1979) has summarized the metabolic changes in dogs undertaking moderate endurance exercise (100 $m \cdot min^{-1}$ on a 15 percent slope) for 3 hours. Most of the energy for this exercise comes either from glucose derived from glycogen in liver and muscle or from FFAs released from adipose tissue. At the onset of exercise, muscle glucose utilization increases, but blood glucose concentrations remain almost constant because exercise induces a decline in blood insulin concentration and a rise in glucagon concentration that stimulate hepatic glycogenolysis and gluconeogenesis (Zinker et al., 1994). Epinephrine release stimulates a sixfold increase in muscle glycogenolysis (Issekutz, 1979). Blood glucose concentrations increase slightly at the onset of exercise because there is an abrupt increase in glucose production associated with an increase in the catecholamine-insulin ratio (Miles et al., 1992). Blood glucose then declines slowly as exercise continues because hepatic glucose production falls slightly behind the uptake of glucose by working muscle (Issekutz, 1979). Epinephrine protects against hypoglycemia during exercise of more than 90-minute duration by inhibiting insulin-stimulated glucose uptake by muscle and enhancing hepatic glycogenolysis (Issekutz, 1979; Moates et al., 1988). Lactate concentrations increase at the onset of exercise because lactate production by the liver increases when the fall in insulin stimulates glycogenolysis and glycolysis in the liver. As exercise progresses, lactate concentrations fall because glucagon and then epinephrine stimulate gluconeogenesis from lactate and the liver becomes a net lactate-consuming organ (Wasserman et al., 1991a).

During exercise, norepinephrine stimulates an increase in the release of FFAs from adipose tissue, and blood FFA concentrations rise gradually (Issekutz, 1979). Glucose production from glycerol in the liver increased ninefold during moderate exercise almost in proportion to the increase in glycerol released from triglycerides, but glucose derived from glycerol remained less than 9 percent of total glucose production (Shaw et al., 1976). The ratio of the release of glucose to that of fat is approximately 1 in dogs at rest but declines to 0.6 after 3 hours of exercise. Since 1 mole of fat provides 3.5 times the energy of 1 mole of glucose, glucose provides less than 20 percent of the energy for exercise, and this contribution declines further as exercise continues (Issekutz, 1979).

Paul and Holmes (1975) summarized the changes in energy provided by oxidation of FFAs and glucose taken up by muscle at rest and during exercise of varying intensity in 10- to 20-kg dogs. At rest, oxidation of plasma FFAs and plasma glucose taken up by muscle provided 23 percent and 26 percent ME, respectively. When these dogs walked on a treadmill at 3 $km \cdot h^{-1}$, energy expenditure was more than double and energy from oxidation of plasma glucose increased but was a smaller part (13 percent ME) of the total. Energy from plasma FFAs, however, increased immediately to 48 percent ME and continued to increase until it was 70 percent ME after 4 hours of walking. When dogs ran at 5-6 $km \cdot h^{-1}$ on a 15 percent slope and energy expenditure increased sevenfold, the results were similar to those of walking dogs. The total amount of plasma glucose oxidized increased but provided a smaller amount of the total (10 percent) ME. Oxidation of plasma FFAs provided 52 percent ME initially, increasing to 70 percent during the last 2 hours of a 4-hour run. At more intense exercise however, an increase in plasma lactic acid concentration inhibits utilization of plasma FFAs by interfering with FFA mobilization from adipose tissue (Issekutz et al., 1964). Thus, when dogs ran at 7.5 $km \cdot h^{-1}$ on a 15 percent slope, which they could manage for only a short duration (60 minutes), energy expenditure increased eightfold, but plasma FFAs and glucose contributed only 21 percent ME and 7 percent ME to the total, respectively. The contribution of plasma FFAs was even lower (12 and 14 percent ME) at rest and during intense short-duration exercise, respectively, in dogs that were untrained. Therriault et al. (1973) also reported that in untrained 22-27-kg mongrel dogs, plasma FFA utilization by muscle was low but found that intramuscular triglyceride provided almost twice as much energy as muscle glycogen during short–duration, intense exercise (7.5 $km \cdot h^{-1}$ on a 17 percent slope) to exhaustion. At lower levels of energy expenditure (7.5 $km \cdot h^{-1}$ on the level), there was still a net utilization of muscle glycogen, but plasma FFAs were taken up

by muscle and there was a net gain in triglyceride within muscle.

In dogs, as in other species, therefore, fat oxidation provides most of the energy at low rates of energy expenditure (60 percent at 40 percent of maximal oxygen uptake; $\dot{V}o_2max$). As exercise intensity increases, glucose oxidation increases and is the principal source of energy at high rates of energy expenditure (80 percent at 85 percent $\dot{V}o_2max$) (Weibel et al., 1996). In dogs, however, the amount of energy from fat oxidation at rest and during exercise is twice that in less aerobic species such as humans and goats (Meyer and Doty, 1988; McLelland et al., 1994). Albumin binds more FFAs in dogs than in less aerobic species, so the concentration of FFAs in the blood is higher and delivery of FFAs to tissues is enhanced (McLelland et al., 1994). Muscle glycogen and fat stores are larger in dogs than in less aerobic species (Weibel et al., 1996). High-carbohydrate diets increase stamina in human athletes by increasing muscle glycogen (Hultman et al., 1994), but high-fat diets appear to increase stamina in dogs undertaking endurance exercise. Downey et al. (1980) found that beagles running on a treadmill with a 7.5 percent slope ran for an average of 20 miles (2.3 hours) before becoming exhausted when fed high-fat (59-81 g per 1,000 kcal ME or 49-63 percent ME as fat) diets containing 63-102 g per 1,000 kcal ME (24-42 percent ME) as protein, but became exhausted after only 15 miles (1.7 hours) when fed a lower-fat (33 g per 1,000 kcal or 26 percent ME as fat) diet containing 58 g per 1,000 kcal ME (23 percent ME) as protein. Feeding a high-fat, low-carbohydrate diet, therefore, appeared to increase stamina. The diet associated with poorer performance, however, contained corn, soybean meal, and wheat as its principal ingredients, whereas the other diets contained soy and animal products. It is possible, therefore, that ingredient composition or lack of some nutrient other than fat may have been responsible for lack of stamina.

Reynolds et al. (1994, 1995) also compared a high-fat (70 g per 1,000 kcal or 58 percent ME), low-carbohydrate (43 g per 1,000 kcal or 15 percent ME) diet to a low-fat (18 g per 1,000 kcal or 14 percent ME), high-carbohydrate (162 g per 1,000 kcal or 59 percent ME) diet in 16 Alaskan husky dogs for 4 weeks before and 12 weeks during training. Both diets contained 27 percent ME (66 g per 1,000 kcal ME) as protein and were composed of similar ingredients except that the high-fat diet contained more lung lobes and beef tallow and less cornstarch. Samples were obtained from dogs before and after a standard aerobic test (1 hour at 14 $km \cdot h^{-1}$ on 0 percent slope) before and after 8 weeks of aerobic training (four 10-km runs at 25 $km \cdot h^{-1}$ each week) and also before and after a standard anaerobic test (3 minutes at 24 $km \cdot h^{-1}$ on a 10 percent slope) before and after 4 weeks of anaerobic training (like the test or pulling an all-terrain vehicle at 16 $km \cdot h^{-1}$). Training increased muscle glycogen irrespective of diet, but the increase in glycogen with training was greater and glycogen was used more rapidly during the anaerobic test after training in dogs fed the high-carbohydrate diet. There was no effect of diet on glycogen utilization during the aerobic test or on lactate accumulation during either test. Plasma FFA concentrations were higher before and after the aerobic test in trained dogs and increased more during the aerobic test in untrained dogs fed the high-fat diet.

These two studies suggest that there is no benefit to dogs of feeding high-carbohydrate diets because the potential benefit of increased glycogen in muscle is overcome by the more rapid use of glycogen during exercise. On the contrary, feeding high-fat diets appears to spare glycogen and improve stamina. Together, they suggest 49 percent ME (59 g per 1,000 kcal ME) as the adequate intake of fat in the diet of dogs undertaking endurance exercise. Nevertheless, well-controlled studies have not evaluated diets containing more than 26 percent and less than 49 percent ME as fat, and it is possible that the fat content of a diet can be reduced below 49 percent ME without any reduction in stamina.

Type of Fat

Miller et al. (1963) reported that exercise increased the plasma concentration of each individual fatty acid in proportion to the plasma concentration of that fatty acid at rest: oleate (18:1), the predominant fatty acid, increased 150 percent, which was more of an increase than palmitate (16:1), which increased more than linoleate (18:2), or stearate (18:0).

Protein and Exercise

"Exercise-Induced Polycythemia" and "Sports Anemia": Hematocrit and Exercise in Dogs

Many studies have observed a reduction in hematocrit after exercise in dogs but the importance of this change is still unclear. In dogs, release of norepinephrine during exercise causes the spleen to contract and release red cells into the circulation, thereby increasing hematocrit (Vatner et al., 1974). Broun (1922) reported that hematocrit and hemoglobin concentration increased initially in dogs climbing a 34 percent slope, but then decreased as exercise continued, while plasma volume increased to compensate for the decline in red cell volume. When dogs were exercised daily for 3-6 days, total blood cell volume declined a mean of 19 percent in dogs that had previously been confined for several weeks, and declined 11 percent in dogs that had been confined only briefly (Broun, 1923a,c). This decline in red blood cell volume stimulated a reticulocyte response and a doubling in size of the spleen, which returned the red cell volume to normal and established a new equilibrium after 3 weeks of daily exercise (Broun, 1923b,c). These dogs were fed "a mixed diet with considerable meat" (Broun, 1922).

Davis and Brewer (1935) also reported that blood volume, cell volume, number of erythrocytes, and hemoglobin

concentration decreased in the blood of dogs during the first week of exercise after confinement but that all of these blood parameters returned to normal or exceeded normal after 4 weeks of exercise, and remained elevated for 4 weeks after exercise had ceased. These dogs consumed a diet of bread, beef lung, and liver, which would have contained approximately 36 percent ME as protein but only 19 percent ME as fat. Analysis of this diet using a computer program (Food Processor for Windows Version 7.81, Database 2001, Esha Research, Salem, Ore.) suggests that the diet conformed to the recommendations of the National Research Council (1985) for a 10-kg dog except for a slight deficiency of vitamin E and magnesium and a marked deficiency of calcium.

Thörner (1932) also found fewer red cells and less hemoglobin in trained dogs than in untrained litter mates and found that the osmotic fragility of the remaining red cells was less in trained dogs, suggesting that fragile cells had disappeared from the circulation. Steinhaus et al. (1932) and Külbs (1912) noted that the bone marrow was redder in exercised dogs than in inactive litter mates. Külbs (1929) noted that there were greater stores of iron in unexercised than in trained dogs. Külbs (1912) found that the spleen increased in size in trained dogs, but Thörner (1930) and Steinhaus et al. (1932) found that the spleen remained the same size or decreased in exercising dogs. More recently, Arokoski et al. (1993) also found that hematocrit, hemoglobin concentration, and erythrocyte count were lower in growing beagles running up to 40 $km \cdot d^{-1}$ on a 15 percent slope than in caged controls. These dogs were fed a diet containing 28 percent ME as protein and 56 percent ME as fat. Mackintosh et al. (1983) showed that blood volume increased 13 percent in beagles fed a "balanced commercial ration" after 3 months running at 7 $km \cdot h^{-1}$ on a 10 percent slope for 1-1.5 hours 5 days a week. Yamada (1987) reported that Shiraki (1968) had found that sports anemia did not develop and red cells were less fragile during vigorous training in splenectomized dogs. Shiraki suggested that there was a hemolytic factor released by the spleen during exercise. Yamada suggested that this factor could be lysolethicin and reported that Tohori et al. (1979) had found that lysolecithin was released by the spleen in response to norepinephrine infusion in dogs that had previously been injected daily with norepinephrine to mimic vigorous training.

Changes in hematocrit that follow the pattern described by Broun have been noted in working and racing dogs. Mean hematocrit increased 0.04 in Labrador retrievers after 10 minutes of repetitive retrieving of a dummy over a distance of 40 m (Matwichuk et al., 1999). Mean hematocrit increased 0.04 in Border collies after a 12-minute combination of intense aerobic and anaerobic exercise (Feldman and Lessard, 1992). Mean hematocrit increased 0.04 in hunting dogs from before to after a 40-minute simulated hunt before the hunting season but did not increase after a 40-minute hunt at the end of the season (Davenport et al., 2001). Mean pre-hunt but not post-hunt hematocrit appeared to have increased 0.04 in these dogs during the hunting season.

Greyhounds have a higher resting hematocrit than other breeds (Porter and Canaday, 1971), but hematocrit has been consistently reported to increase from before to after racing (Snow et al., 1988; Ilkiw et al., 1989; Rose and Bloomberg, 1989; Nold et al., 1991; Hill et al., 2000, 2001b) and to decrease below resting levels by 1 to 3 hours after a race (Ilkiw et al., 1989; Rose and Bloomberg, 1989). Resting hematocrit did not change significantly in greyhounds, however, after 14 days of training at moderate intensity on a treadmill or during a 4-month racing season (McKeever et al., 1985; Lassen et al., 1986). Total hemoglobin in the blood did increase 26 percent after 14 days of training on the treadmill, however, because mean plasma volume and blood volume increased 27 percent and 21 percent, respectively (McKeever et al., 1985). Mean hematocrit also increased in Alaskan huskies immediately after a 9-km run pulling an all-terrain vehicle in teams of 12 dogs, but mean hematocrit decreased 0.08 during 6 months of training (Querrengaesser et al., 1994). Mean hematocrit declined in Alaskan sled dogs from 0.60 before to 0.46 less than 1 hour after finishing a 480-km race (Hinchcliff et al., 1997a).

Exercise, therefore, appears to cause a transient polycythemia and then a temporary anemia followed by a return to normal and an increase in blood volume above normal. Red cell synthesis is stimulated, and the increased synthetic demands on spleen and bone marrow could make hematocrit a sensitive indicator of nutritional adequacy, especially of protein. It should be noted, however, that hematocrit can also decline if plasma volume increases and a decline in hematocrit does not necessarily mean a decline in red cell mass.

A reduction in hematocrit could affect performance by limiting the oxygen-carrying capacity of the blood. Wu et al. (2001) found that pulmonary function increased with hematocrit during exercise in dogs and postulated that the increase in pulmonary diffusing capacity and pulmonary blood flow associated with exercise-induced polycythemia could explain why trained dogs have such a high $\dot{V}O_2max$ compared to elite human athletes. During exercise at 50 percent $\dot{V}O_2max$, plasma glucagon, epinephrine, norepinephrine, cortisol, and lactate concentrations all increased more in anemic dogs with a 25 percent reduction in hematocrit than in dogs that were not anemic (Wasserman et al., 1985). Hepatic glucose production also increased, but plasma glucose concentrations declined more rapidly during exercise in anemic dogs because blood glucose was cleared more rapidly. This suggests that stamina could be compromised by a reduction in hematocrit. The $\dot{V}O_2max$ was unaffected, however, by a 25 percent decrease in hematocrit in splenectomized dogs because systemic resistance decreased and cardiac output increased, which compensated for the decrease in oxygen content of arterial blood (Horstman et al., 1974). The importance of the small reduc-

tions in hematocrit reported during nutritional studies therefore remains uncertain.

Protein Metabolism During Exercise

Protein and amino acid synthesis and catabolism increase in exercising dogs. Synthesis increases to accommodate the changes associated with training and to replace protein and amino acids catabolized during exercise. Protein and amino acids are catabolized during exercise as a source of energy and as precursors of gluconeogenesis.

Okamura et al. (1997) reported that total plasma amino acid concentrations decreased 15 percent and concentrations of glutamine, arginine, lysine, and gluconeogenic amino acids such as alanine, glycine, serine, and threonine decreased 15-50 percent during exercise of moderate intensity, but concentrations of branched-chain amino acids such as leucine did not change and tyrosine and phenylalanine concentrations increased. During recovery, glutamine concentrations increased 10 percent and branched-chain amino acids increased 18 percent.

Wasserman et al. (1987, 1988, 1989a,b) showed that gluconeogenesis increased over time in 21-kg mongrel dogs undertaking moderate endurance exercise (running for 2.5 h at 6 $km \cdot h^{-1}$ on a 12 percent slope). Glucose utilization doubled initially and then increased further until it was three times normal, but blood glucose concentrations remained relatively constant because hepatic glucose production increased in tandem with glucose utilization. Hepatic glucose production increased because hepatic glycogenolysis and gluconeogenesis were stimulated by a fall in circulating insulin and a gradual increase in blood glucagon concentrations to twice normal. Gluconeogenesis from alanine increased gradually during 2.5 hours of exercise until it was three times normal because fractional extraction of alanine by the liver and channeling of alanine toward gluconeogenesis within the liver both gradually increased over the 2.5 hours of exercise. Gluconeogenesis from alanine increased further during recovery as delivery of alanine to the liver increased above that during exercise and fractional excretion of alanine remained high. Lactate was released by the liver at the start of exercise in response to the initial fall in insulin but was then taken up by the liver and also used as a gluconeogenic precursor as glycogen concentrations decreased.

These and other studies show that gluconeogenesis plays a more important role in prolonged exercise of moderate intensity than in episodes of more intense activity. Coker et al. (1997) showed that net hepatic alanine uptake decreased and arterial lactate concentrations increased during a short period (20 minutes) of more intense exercise (85 percent of maximal heart rate), presumably because there was greater hepatic glycogenolysis and glycolysis and less gluconeogenesis. Wasserman et al. (1992), however, showed that there was a transition to a "more gluconeogenic mode" during prolonged exercise in dogs. Initially during exercise of moderate intensity, glucose consumed by working muscle was mostly oxidized, but after 30 minutes, nonoxidative glucose utilization increased leading to an increased release of the gluconeogenic precursors lactate, pyruvate, and glutamine. Limb glycolysis increased immediately at the onset of exercise but reached a peak at the end of exercise. Hepatic uptake of lactate increased in proportion to the increased release by muscle. Lipolysis increased immediately, but FFA concentrations increased more gradually. The increase in FFA concentrations occurred at the same time as the increase in gluconeogenesis and provided energy for gluconeogenesis within the liver.

The precursors for gluconeogenesis are mobilized from the gut and adipose tissue as well as from muscle. Shaw et al. (1976) showed that hepatic glucose synthesis from glycerol released from adipose tissue by lipolysis increased ninefold during moderate endurance exercise in dogs. Ammonia generated in exercising muscle by oxidation of branched-chain amino acids and deamination of AMP is shuttled to the gut and liver as glutamine and alanine (Wasserman et al., 1991b). Glutamine taken up by the gut is either oxidized or released as glutamate. Alanine, glutamate, glutamine, and other amino acids are taken up by the liver, where their carbon skeletons may be oxidized or used for gluconeogenesis, while nitrogen is used for synthesis of amino acids or nucleotides or for ureagenesis (Wasserman et al., 1991b). Wasserman et al. (1991b) showed that glutamine was the most important carrier in exercising dogs, with splanchnic uptake four times that of alanine. Glutamine uptake by the gut doubled and glutamine uptake by the liver increased more than fourfold during 150 minutes of moderate-intensity exercise. Glutamate and ammonia release by the gut and hepatic uptake increased in parallel during exercise, and urea synthesis by the liver doubled, but there was net gut proteolysis because α-amino nitrogen release by the gut exceeded glutamate output. Williams et al. (1996) also showed that release of the branched-chain amino acid leucine, primarily by the intestine, increased gradually during 90 minutes of moderate-intensity exercise until it was 30 percent above normal. Blood concentrations of leucine did not change because leucine uptake, presumably by exercising muscle, increased in tandem with increased release. Labile proteins in the gut appear to be mobilized as a source of amino acids, therefore, to attenuate protein catabolism in muscle before and after exercise. Halseth et al. (1997) showed that gut and liver provided 40 percent of total body proteolysis as measured by leucine turnover during both rest and exercise. Liver and gut were equally important at rest and during exercise 42 hours after feeding, but proteolysis in the gut was more important in dogs exercised 18 hours after a meal.

These studies demonstrate that protein utilization is greater in exercising than in sedentary dogs but increases with the duration of exercise. Protein requirements are probably greater, therefore, for dogs undertaking long-distance

endurance exercise of moderate intensity of more than 30 minutes' duration than for dogs undertaking more intense exercise for 20 minutes or less.

Protein in the Diet of Exercising Dogs

Arokoski et al. (1993) successfully fed growing beagles a commercial diet containing 28 percent ME (67 g per 1,000 kcal ME) as protein and 56 percent ME (67 g per 1,000 kcal ME) as fat from 16 to 70 weeks of age when dogs were exercised on a treadmill with a 15 percent slope 5 days per week, with the distance and speed gradually increasing to 40 $km \cdot d^{-1}$ and 5-7 $km \cdot h^{-1}$ by 1 year of age. Young et al. (1962) measured urinary excretion of nonprotein nitrogen, amino acids, and ammonia 17 hours after a meal containing 19 percent ME as fat and 29 percent ME as protein in trained young adult beagles either at rest or when undertaking 3 hours of aerobic exercise (at approximately 50 percent $\dot{V}O_2max$). During exercise, dogs excreted approximately 1 g nonprotein nitrogen in their urine per 1,000 kcal expended, which was equivalent to only 2.5 percent ME as protein. At rest, dogs excreted approximately 7 g nonprotein nitrogen in their urine per 1,000 kcal, which is equivalent to 18 percent ME as protein. The mean rate of urinary excretion of taurine was doubled during exercise from 19 to 43 $\mu mol \cdot h^{-1}$ and of cystathionine decreased during exercise from 3 to 1 $\mu mol \cdot h^{-1}$, but rates of excretion of other essential amino acids, ammonia, methylhistidine, and nonprotein nitrogen were the same in dogs at rest and during exercise. Relative to energy expended, however, urinary excretion of these nutrients was much reduced because exercising dogs expended nine times more energy (200 vs. 23 $kcal \cdot h^{-1}$) than resting dogs.

Reynolds et al. (1999) examined the effect of increasing dietary protein from 48 to 90 g per 1,000 kcal ME (19 to 36 percent ME) and decreasing carbohydrate from 98 to 52 g per 1,000 kcal ME (36 to 19 percent ME) on Alaskan sled dogs during intensive training of 12 weeks duration (assuming 1.5 percent DM crude fiber in each diet). Dietary fat was maintained between 54 and 58 g per 1,000 kcal ME (45-47 percent ME), and similar ingredients were used for all four diets. Dogs were run 15 km at 25-27 $km \cdot h^{-1}$ four times weekly for 8 weeks and then had two maximal and two submaximal runs on a treadmill weekly for 4 weeks. The $\dot{V}O_2max$ was 25 percent lower and the rate of soft tissue injury was eight times higher in dogs fed the 48 g per 1,000 kcal ME (19 percent ME) as protein diet compared to dogs fed diets containing 60 g per 1,000 kcal ME (24 percent ME) or more as protein. Plasma volume was 10 percent higher in dogs fed the 90 g per 1,000 kcal ME (36 percent ME) as protein diet compared to dogs fed diets containing 75 g per 1,000 kcal ME (30 percent ME) or less as protein. There were slight increases in mean hematocrit and hemoglobin concentrations, and total red blood cell volume and total blood volume increased linearly with protein intake. Querengaesser et al. (1994) increased protein in the diet of Alaskan huskies from 72 to 85 g per 1,000 kcal ME (from 29 to 35 percent ME), decreased fat from 69 to 63 g per 1,000 kcal ME (from 57 to 52 percent ME), and kept NFE unchanged. Mean resting hematocrit declined a similar amount (0.08) in dogs fed both diets during 6 months of training during which dogs ran 1,200 km, but hematocrit increased after exercise only in dogs fed the higher-protein diet, lower-fat diet.

Hill et al. (2001b) showed that, among greyhounds racing more than 500 m twice weekly, dogs ran 0.3 $km \cdot h^{-1}$ faster and hematocrit was 0.02-0.03 higher when dogs were fed a lower-protein (63 g per 1,000 kcal or 24 percent ME) and higher-carbohydrate (106 g per 1,000 kcal or 43 percent ME) diet compared to when they were fed a higher-protein (96 g per 1,000 kcal or 37 percent ME) and lower-carbohydrate (75 g per 1,000 kcal or 30 percent ME) diet. These diets contained similar amounts of fat (36 g per 1,000 kcal or 33 percent ME) and similar ingredients, but rice and corn were increased in the lower-protein diet at the expense of soy protein, corn gluten, egg, and poultry meal. Dogs were fed the lower-protein diet for 11 weeks. The amino acid composition of this low-protein diet (Table 11-11) represents an adequate intake (AI) for sprinting dogs. For greyhounds whose food intake is restricted 10 percent, these values may need to be increased 10 percent. These amounts of amino acids are probably not adequate for sled dogs undertaking endurance exercise.

Yamada et al. (1987) found that among mongrel dogs running 12 $km \cdot h^{-1}$ for 4 hours daily, "sports anemia" was greater in dogs fed a vegetable (soybean) protein diet compared to dogs fed an animal (fish and meat meal) protein diet. Both diets contained 35 percent ME as protein and 17-18 percent ME as fat. Red cell fragility increased and hematocrit declined after 3 weeks of exercise in dogs fed the vegetable

TABLE 11-11 Adequate Intake of Amino Acids for Greyhounds[a]

Amino Acid	Intake (g per 1,000 kcal ME)
Arginine	3.5
Histidine	1.3
Isoleucine	2.3
Leucine	5.8
Lysine	2.7
Cystine	0.9
Methionine	1.1
Tyrosine	2.2
Phenylalanine	2.8
Threonine	2.2
Tryptophan	0.5
Valine	2.8

[a]Derived from a study in which a diet containing 4,400 kcal $ME \cdot kg^{-1}$ DM was fed free choice to trained racing greyhounds with an average body weight of 33 kg consuming 154 kcal $ME \cdot kg\ BW^{-0.75}$.

protein diet but not in dogs fed the animal protein diet. This change in red cell fragility correlated with a fall in serum and red cell cholesterol and an increase in red cell lysolecithin. These authors attributed the decline in cholesterol and increase in lysolecithin and phospholipid during exercise to the action of lecithin-cholesterol acyltransferase (LCAT), which catalyzes transfer of a fatty acyl group from lecithin to cholesterol to form lysolecithin and cholesterol ester. They postulated that increased lysine in the animal protein diet prevented these lipid changes. Nevertheless, lysine cannot provide the entire explanation because greyhounds in the study by Hill et al. (2001b) that were fed a higher-protein diet consumed more lysine and more animal protein but had a lower hematocrit than did dogs fed the lower-protein diet.

Studies That Have Altered Both Fat and Protein in the Diet of Exercising Dogs

Several studies have examined the effect on exercising dogs of feeding diets in which both fat and protein are increased at the expense of carbohydrate. Many of these studies also change major ingredients and sources of protein, fat, or carbohydrate. It is often uncertain, therefore, whether it is the increase in protein, the increase in fat, the decrease in carbohydrate, or a change in some other ingredient that is responsible for any change observed.

Adkins and Kronfeld (1982), for example, reported that among dogs that suffered a bout of diarrhea while running in the Iditarod, red blood cell counts declined less in dogs fed a diet with more protein (74 g per 1,000 kcal or 30 percent ME), more fat (81 g per 1,000 kcal or 67 percent ME), and less carbohydrate (9 g per 1,000 kcal or 3 percent ME) than in dogs fed a diet containing less protein (62 g per 1,000 kcal or 24 percent ME), less fat (68 g per 1,000 kcal or 54 percent ME), and more carbohydrate (64 g per 1,000 kcal or 22 percent ME). Davenport et al. (2001) found that English pointers performed less well when hunting (fewer finds per hunt) and lost weight when consuming a diet containing less protein (68 g per 1,000 kcal or 26 percent ME) and less fat (45 g per 1,000 kcal or 35 percent ME) compared to one containing more protein (74 g per 1,000 kcal or 29 percent ME) and more fat (51 g per 1,000 kcal or 41 percent ME).

Kronfeld (1973) reported that 2- to 6-year-old crossbred husky dogs tended to eat their own feces and developed a "tying up" stiff-legged syndrome during work when fed a commercial dog food containing, in "percent energy equivalent," 29 percent protein, 32 percent fat, and 39 percent carbohydrate. Coprophagy disappeared and stamina improved in these dogs when horsemeat was added to the commercial food. Adding horsemeat increased energy intake by 25 percent, decreased dietary carbohydrate from 39 to 22 percent (energy equivalent), increased dietary protein from 29 to 33 percent (energy equivalent), and increased dietary fat from 32 to 45 percent (energy equivalent). A further subjective improvement in stamina was described when dogs were fed a commercial chicken product containing 34 percent protein, 64 percent fat, and no carbohydrate (energy equivalent).

Kronfeld et al. (1977) and Hammel et al. (1977) blended a canned diet made from whole chicken and pork lungs (containing almost no carbohydrate) with a dry diet consisting mostly of ground corn and soybean meal (129 g per 1,000 kcal or 46 percent ME as carbohydrate) to produce three diets in which dietary protein increased from 75 to 102 g per 1,000 kcal ME (from 29 to 41 percent ME) and dietary fat increased from 41 to 71 g per 1,000 kcal ME (from 33 to 58 percent ME). These diets were fed to racing cross-bred Alaskan huskies during 24 weeks of training, during which dogs ran 1,100 km. Mean hematocrit and red cell count increased during training in all dogs. These high red cell indices were maintained in dogs fed diets containing 88 g per 1,000 kcal ME (35 percent ME) or more protein, 55 g per 1,000 kcal ME (44 percent ME) or more fat, and less than 21 percent ME (59 g per 1,000 kcal ME) carbohydrate, but hematocrit and red cell numbers declined very slightly (0.02 and $5 \times 10^6 \cdot mL^{-1}$, respectively) during training in dogs fed the diet containing 75 g per 1,000 kcal ME (29 percent ME) as protein, 41 g per 1,000 kcal ME (33 percent ME) as fat, and 107 g per 1,000 kcal ME (38 percent ME) as carbohydrate. No evidence of a hematological abnormality was detected in any of the dogs fed these high-protein and fat diets for 6 months. Peak plasma concentrations of FFAs after exercise increased with increasing dietary fat, but there was no difference in resting plasma glucose concentrations, peak concentrations after exercise, or most other parameters among the three diets.

Toll et al. (1992) reported that greyhounds ran 0.4 $km \cdot h^{-1}$ faster over 500 m during the fifth week of feeding a higher-carbohydrate (52 percent DM), lower-fat (16 percent DM) diet than when they were fed a lower-carbohydrate (8 percent DM), higher-fat (56 percent DM) diet. Diets were "otherwise similar in composition." If these diets are assumed to contain approximately 6 percent DM ash and 2 percent DM crude fiber, then the percent ME from protein, fat, and carbohydrate, respectively, would be 23, 31, and 46 percent in the higher-carbohydrate, lower-fat diet and 19, 75, and 6 percent in the lower-carbohydrate, higher-fat diet. Hill et al. (2000), however, showed that among greyhounds racing more than 500 m twice weekly, dogs ran 0.4 $km \cdot h^{-1}$ faster and hematocrit was 0.04 higher when dogs were fed a higher-protein (67 g per 1,000 kcal or 25 percent ME), higher-fat (36 g per 1,000 kcal or 32 percent ME), and lower-carbohydrate (105 g per 1,000 kcal or 43 percent ME) diet than when they were fed a lower-protein (59 g per 1,000 kcal or 21 percent ME), lower-fat (29 g per 1,000 kcal or 25 percent ME), and higher-carbohydrate (135 g per 1,000 kcal or 54 percent ME) diet. Diets contained similar ingredients, but the higher-fat diet contained more poultry meal and less wheat. Since the study by Hill et al. (2001b) suggests that in-

creasing protein does not improve performance in racing greyhounds, it is likely that the changes in relative proportions of dietary fat and carbohydrate affected the performance of these greyhounds.

Together, all of these studies suggest an AI for dogs undertaking endurance exercise of 90 g per 1,000 kcal or 35 percent ME for protein and 59 g per 1,000 kcal or 49 percent ME for fat, and an AI for fed greyhounds undertaking sprint exercise of 60 g per 1,000 kcal or 24 percent ME for protein and 36 g per 1,000 kcal or 30 percent ME for fat. For greyhounds whose intake is being restricted 10 percent, these values may need to be increased 10 percent. The amount of protein in the diet should be increased proportionately as the duration of exercise increases above 30 minutes. It is possible, however, that dogs undertaking endurance exercise may perform well when consuming slightly less than 49 percent ME fat and sprinting dogs may run even faster when fed a diet containing more than 30 percent ME as fat (but less than 75 percent ME as fat) or when fed a diet containing less than 24 percent ME as protein. Untrained dogs may also require less fat.

There are no studies of the effect of protein, fat, and carbohydrate on exercise in cats. Cats are sprinters and would be expected to have a requirement for large stores of glycogen in muscle, but are adapted to a diet that is high in protein and fat and low in carbohydrate. Experiments with sedentary cats suggest that feline metabolism is little affected by changes in the composition of the diet, and it is unlikely that exercise greatly affects requirements for protein, fat, or carbohydrate in exercising cats.

Dietary Carbohydrate and Exercise

Kronfeld et al. (1977) and Hammel et al. (1977) reported that Alaskan husky cross-bred dogs remained healthy, performed well with no major changes in blood parameters, and did not become hypoglycemic either before or after exercise when fed a diet containing almost no carbohydrate (1 g per 1,000 kcal ME of NFE) and only 3 g per 1,000 kcal ME (2 percent DM) of crude fiber. This diet was very high in protein (102 g per 1,000 kcal or 41 percent ME as protein) however, and it is possible that more carbohydrate may be required when a diet contains fewer amino acid precursors for gluconeogenesis. Kronfeld (1973) also described working sled dogs performing well when fed a commercial chicken diet containing no "energy equivalent" as carbohydrate and 34 percent of energy equivalent as protein. Dogs fed this diet were reported to have "loose, pasty or fatty feces" when given their food as a single large meal, but not when the diet was divided into two meals daily. Decombaz (1995) reported that sled dogs were fed a diet containing no carbohydrate and 28 percent ME as protein during 9 days of the Alpirod with no ill effects. Thus, there appears to be no requirement for digestible carbohydrate in dogs provided enough protein is given to supply the precursors for gluconeogenesis.

In greyhounds, muscle glycogen declines markedly during a race, but most muscle fibers are of the high oxidative type (Rose and Bloomberg, 1989). Some authors have suggested that carbohydrate may improve performance (Gannon, 1987), but high-fat diets may also increase maximal fat oxidation, total maximal energy expenditure, and performance in greyhounds. Toll et al. (1992) reported that greyhounds ran slower when the carbohydrate content of the diet decreased from approximately 46 percent to 6 percent ME in exchange for dietary fat. Hill et al. (2000, 2001b) showed that greyhounds ran faster when dietary carbohydrate was increased from 30 to 43 percent ME (from 75 to 106 g per 1,000 kcal ME) in exchange for dietary protein, but ran slower when dietary carbohydrate was increased from 43 to 54 percent ME (from 105 to 135 g per 1,000 kcal ME) in exchange for dietary protein and fat. These studies suggest that increasing dietary carbohydrate improves the performance of racing greyhounds, but there is a point at which the benefit from increasing carbohydrate is outweighed by the decrease in performance from decreasing dietary fat.

The potential health benefits of fermentation of resistant starch and soluble fiber in the colon have been discussed elsewhere. It is probably preferable that some indigestible fermentable carbohydrate passes through the small intestine of racing dogs to be fermented in the colon, but there have been no experiments in exercising dogs to determine how much this should be. Rapid fermentation of oligosaccharides, for example, may decrease colonic pH and inhibit clostridial growth promoted by feeding meat (Amtsberg et al., 1989). Fructooligosaccharides inhibit cecal colonization by *Salmonella* spp. in chickens and may also do so in dogs fed raw meat (Bailey et al., 1991). Biourge (1995) reported that the mean total dietary fiber content of seven commercial diets recommended for sled dogs was 6.5 percent (range 5.7-7.8 percent). Fiber sources were cereals or added ingredients such as beet pulp or corn fiber. Grandjean and Paragon (1993b) recommended that fiber should be included in minimal amounts in diets for exercising dogs because fiber is bulky, lowers the digestibility of the diet, and increases fecal water excretion, thereby promoting dehydration. Undigested protein may also provide a substrate for fermentation in dogs fed very high protein diets. In conclusion, some indigestible fermentable carbohydrate in the diet is probably beneficial, but the ideal amount is uncertain.

Importance of Water and Water Requirements at High Ambient Temperatures

High body temperatures can be lethal. Adolph (1947) reported that dogs and cats died when rectal temperatures increased above 41 and 42°C, respectively; the median temperature at which the animals died was 41.7°C for dogs and 43.4°C for cats. Dogs and cats were able to tolerate ambient temperatures of 56°C for at least 3 hours in an atmosphere

with 23 percent relative humidity, but lost their ability to keep cool in 100 percent humidity. Evaporative cooling by panting was the major factor that determined their ability to keep cool. Animals lost 1-2 percent $BW \cdot h^{-1}$ at the highest ambient temperatures they were able to tolerate, which suggests that the water requirement at very high ambient temperatures must be 2 percent $BW \cdot h^{-1}$ (20 $mL \cdot kg\ BW^{-1} \cdot h^{-1}$). Dogs and cats did not drink continuously, however, when allowed free access to water in an ambient temperature of 48°C, but allowed up to 9 percent dehydration to develop before drinking.

Adolph (1947) calculated that if animals evaporating water at a rate of 1 percent $BW \cdot h^{-1}$ lost the ability to evaporate water, their body temperature would increase $7°C \cdot h^{-1}$. Conversely, he observed that cats could cool themselves at a similar rate when placed in a favorable environment. He also observed that dogs and cats became intolerant to heat and rectal temperatures increased "explosively" when dogs became 11-20 percent dehydrated and cats became 17-23 percent dehydrated. None of these changes developed when drinking water was available.

Baker (1984) and Doris and Baker (1981) also showed that normally hydrated dogs and cats were able to maintain body temperature up to 45°C in air of 13-47 percent relative humidity. Mean evaporative losses in dogs and cats are shown in Table 11-12. Water requirements increased approximately 6 $mL \cdot kg\ BW^{-0.75} \cdot d^{-1} \cdot °C^{-1}$ above 30°C in dogs and increased 8-12 $mL \cdot kg\ BW^{-0.67} \cdot d^{-1} \cdot °C^{-1}$ above 35°C in cats. At an ambient temperature of 45°C, water requirements increased twofold above normothermic levels in dogs and three- to sevenfold above normothermic levels in cats.

The same authors also showed that dehydrated dogs and cats conserved water by allowing their body temperature to rise almost 1°C at ambient temperatures of 35-45°C. This increase in body temperature increased the temperature gradient with the environment, enhanced heat loss, and reduced evaporative losses. In dehydrated dogs, evaporative losses decreased by approximately 50 percent, panting by approximately 100 breaths per minute, and cardiac output by 30 percent. In dehydrated cats, body temperature increased similarly, but panting and evaporative water losses declined only at ambient temperatures of 35 and 38°C, not at higher ambient temperatures.

In summary therefore, dogs and cats require free access to water to maintain normal body temperature in high ambient temperatures. Water requirements double in dogs and increase up to sevenfold in cats at an ambient temperature of 45°C. As much as 20 $mL \cdot kg\ BW^{-1} \cdot h^{-1}$ may be required at higher ambient temperatures. Dogs and cats are able to survive, however, when consuming slightly less water because they are able to conserve body water by allowing their body temperature to rise slightly when they become dehydrated.

Exercise-Induced Hyperthermia and the Importance of Water During Exercise

Heat is generated during exercise because work is an inefficient process. Unless this heat is lost to the environment, rectal body temperature tends to rise. In a warm environment, evaporative cooling by panting is the primary means of losing heat. Dogs respond to a warm environment by peripheral vasodilatation to promote heat dissipation, but they are unable to lose this heat by sweating because dogs sweat only on their paws (Hammel et al., 1958). Only in a cold environment can dogs and cats lose heat by radiation and convection. Rice and Steinhaus (1931) reported that mongrel

TABLE 11-12 Daily Water Loss from Hydrated and Dehydrated Dogs and Cats as Affected by Temperature

Subjects	*n*	BW (kg)	Ambient Temperature (°C)	Mean Daily Water Loss ($mL \cdot kg\ BW^{-0.75}$ in dogs; $mL \cdot kg\ BW^{-0.67}$ in cats)		Reference
				Hydrated	Dehydrated	
Male and female mongrel dogs	7	32 ± 3	25	119	44	Baker, 1984
			35	152	70	
			40	196	103	
			45	214	136	
Male and female domestic cats	9	3-5	35	42	25	Doris and Baker, 1981
			38	59	35	
			40	91	90	
			45	130	163	
Female short-haired domestic cats	5	2-3	20	27		Adams et al., 1970
			26	24		
			32	21		
			35	35		
			38	62		
			41	137		

dogs running at normal room temperature or swimming in 40°C water developed a respiratory alkalosis from panting in response to a gradually mounting temperature. Dogs swimming in water at less than 20°C developed an acidosis and a declining temperature, and dogs swimming in 20-30°C water showed no change in blood pH or temperature until close to exhaustion. Thus, losing heat was an overriding concern in a warm environment where the heat generated by exercise was greater than that being lost to the environment. In a cold environment, dogs increase their metabolic rate to maintain body temperature *at rest* (Grandjean and Paragon, 1993a). Exercise reduces the need to generate heat to maintain body temperature, and as the level of activity increases, maintaining a *low* body temperature and *losing* heat once again become overriding concerns.

Several authors have noted that a high ambient temperature limits exercise capacity in dogs. Dill et al. (1932, 1933) noted that dogs were able to travel further in a cool than in a warm environment and that rectal temperature as well as lactate concentrations increased as dogs became exhausted. Young et al. (1959b) found that the rate of increase of rectal temperature increased with the intensity of work and that the maximum duration of a run was proportional to the time required for rectal temperature to reach 41°C. Weibel et al. (1983) reported having to reduce ambient temperature to 5°C to prevent rectal temperatures from rising too high when dogs ran faster than $\dot{V}O_2max$. Pohoska (1979) found that the rise in rectal temperature during exercise was attenuated and dogs ran for twice as long when mongrel dogs were cooled while running. Kruk et al. (1985) and Kozlowski et al. (1985) reported that cooling mongrel dogs with ice packs while they ran at 6 $km \cdot h^{-1}$ on a 21 percent slope in an ambient temperature of 22°C increased the mean time to exhaustion by 45-62 percent, reduced the mean rectal temperature at exhaustion by 1°C, and decreased heart rate, respiratory rate, and blood lactate concentrations slightly. The muscle content of ATP and creatine phosphate decreased less, glycogen concentrations in muscle declined more slowly, and muscle concentrations of AMP, pyruvate, and lactate increased less in cooled dogs. This suggests that increasing body temperature lowers the energy balance between high- and low-energy phosphagens and decreases endurance by increasing the rate of glycolysis.

Taylor et al. (1971) reported that African hunting dogs maintain a higher temperature than domestic dogs during exercise in a hot environment to minimize their evaporative losses. Some studies suggest that dehydrated dogs also allow body temperature to rise higher during exercise to minimize water losses but at the risk of body temperature rising too high and reducing endurance. Baker et al. (1983) reported that in dehydrated domestic dogs, rectal temperature was 0.5°C higher at the end of 30 minutes of moderately heavy exercise and the amount of fluid drooled by dogs during exercise was 90 percent less compared to normally hydrated dogs, but the rate of increase in rectal temperature during exercise was not affected by dehydration. Greenleaf et al. (1974) reported that increasing plasma sodium concentration and osmolality by infusing hypertonic saline before or during 60 minutes of exercise increased the rectal temperature of dogs 0.3°C before and during exercise. Young et al. (1959a) found that provision of water to adult beagles undertaking moderately intense exercise reduced the rectal temperature at the end of exercise from 40.9 to 40.1°C, reduced the mean loss of body weight during exercise from 11 to 7 percent, decreased the average increase in hematocrit associated with exercise from 21 to 3 percent, and increased endurance by 80 percent. Dill et al. (1932) commented that body temperature does not rise and a dog is virtually tireless during submaximal exercise when the ambient temperature is low and food and water are provided.

In summary, therefore, exercise-induced hyperthermia limits the capacity of dogs to exercise. Dehydration increases body temperature slightly during exercise, whereas free access to water minimizes exercise-induced hyperthermia and markedly improves stamina.

Water Requirements at Rest and During Exercise

Animals have access to three sources of water: free water that they drink, water in their food, and water generated during metabolism. Metabolic water provides 0.41, 1.07, and 0.6 $mL \cdot g^{-1}$ (0.1, 0.12, and 0.15 $mL \cdot kcal\ ME^{-1}$) from protein, fat, and carbohydrate, respectively (Rowntree, 1922). The metabolic water in a mixed diet, therefore, provides approximately 0.12 $mL \cdot kcal\ ME^{-1}$. This metabolic water will mitigate some of the water losses during a run, but will be partly balanced by loss of water in feces. Water that is drunk and water in food are the primary subjects of this discussion because they can be varied separately from the composition of the food. Total water intake for the purpose of this discussion, therefore, refers to the sum of drinking water and water in food.

Adolph (1939) reported that four dogs in cages took in a mean of 0.79 (range 0.61-0.91) $mL \cdot kcal^{-1}$ ME as free water and in food (109 ± 21 $mL \cdot kg\ BW^{-0.75} \cdot d^{-1}$ as free water and 3 ± 3 $mL \cdot kg\ BW^{-0.75} \cdot d^{-1}$ in food). English and Filippich (1980) reported that dogs in 1-m^3 cages took in a mean of 0.56 (range 0.51-0.67) $mL \cdot kcal^{-1}$ ME as free water and in food (109 ± 26 $mL \cdot kg\ BW^{-0.75} \cdot d^{-1}$ as free water and 8 ± 1 $mL \cdot kg\ BW^{-0.75} \cdot d^{-1}$ in food). Van Limborgh and Van der Wind (1972) reported that water intake (free water and in food) was between 0.6 and 1 $mL \cdot kcal^{-1}$ ME in sedentary adult beagles and weaned pups. All reports, however, describe considerable day-to-day and dog-to-dog variation in intake, with some animals on some days taking in more than twice the mean. At least twice the mean amount of water reported here should therefore be made available to sedentary animals daily.

Dry food contains little water (approximately 0.1 $mL \cdot g^{-1}$ as fed or 0.03 $mL \cdot kcal^{-1}$ ME), whereas canned food or meat

contains much more (0.7-0.8 mL·g^{-1} as fed or approximately 0.2 mL·kcal^{-1} ME). Dogs adjust the amount of water that they drink, however, to balance the amount of water in food (Ramsay and Thrasher, 1991). Cizek (1959) reported that as water in the food fed to dogs increased, total water intake remained constant at 30 mL·kg BW^{-1}·d^{-1} because dogs drank less. Only as water in the food approached and then exceeded 30 mL·kg BW^{-1} did total intake exceed 30 mL·kg BW^{-1}·d^{-1}. Dogs consuming dry food, therefore, drink approximately 0.2 mL·kcal^{-1} ME more free water than dogs consuming wet food. Cizek (1959) also showed that dogs continue to drink a minimal amount of water (6 mL·kg BW^{-1}·d^{-1}) even when taking in an abnormally high amount of water in the food.

Drinking water is an intermittent process at rest and during exercise for dogs, but loss of water is a continuous process. Robinson and Adolph (1943) found that dogs at rest given free access to water did not sip it continuously but drank after losing about 0.5 percent BW. Dogs drank only enough water to replace 0.2-0.4 percent BW and body weight did not return to baseline until after a meal. When water was withheld for a period, however, dogs drank as soon as it was presented, often earlier than they would normally have done if offered free-choice water. Gregersen (1932) noted that dogs consumed most of their water within 2-5 hours of eating but that this postprandial thirst was temporary; dogs drank much less each day when water was withheld for several hours after each meal. Starved animals drank 66-80 percent less water (Kleitman, 1927). It is not recommended that water be withheld after a meal, however, because increased water intake after a meal balances a tendency to lose weight between meals.

Dogs with free access to water regulate their osmolality by adjusting water intake to balance the amount of water lost in urine and by evaporation, not by altering the concentration of their urine (O'Connor and Potts, 1969; Ramsay and Thrasher, 1991). Urine production and total water intake, therefore, increase in proportion to the amount of solute that must be excreted (i.e., with the amount of salt, protein [excreted as urea], and dry matter in the diet; Danowski et al., 1944; Ramsay and Thrasher, 1991). Mean water intake of 13-kg sedentary beagles increased from 0.64 to 0.9 mL·kcal^{-1} ME when sodium increased in the diet from 1 to 2.5 g per 1,000 kcal ME (Baker, 1984). Mean water intake increased in sedentary 18- to 20-kg mongrel dogs from 99 to 210 mL·kg BW$^{-0.75}$·d^{-1} (from 0.55 to 1.16 mL·kcal^{-1}) when sodium intake increased from 76 to 505 mg·kg BW$^{-0.75}$·d^{-1} (Cowley et al., 1983). Mean total water loss increased from 17 to 26 mL·kg BW^{-1}·d^{-1} when protein consumed increased from 1.5 to 4 g·kg BW^{-1}·d^{-1} in sedentary dogs (Danowski et al., 1944). Water requirements can double, therefore, when salt and protein intake is increased. Increased protein and salt intake also enhances the rate of dehydration if water is withheld during exercise.

O'Connor and Potts (1969) reported that dogs in kennels took in a mean of 0.64 (range 0.44-1.24) mL·kcal^{-1} ME as free water and in food, but that mean evaporative loss (1 g·kg BW^{-1}·h^{-1} at rest to 5 g·kg BW^{-1}·h^{-1}) and water intake (4 to 109 mL·kg BW^{-1}·d^{-1}) varied with activity, the most active dogs losing and drinking the most water. Dogs drank mostly small volumes (30 to 100 mL) during times of day when they were most active, but drank larger quantities after a period of water deprivation. Urine volume was unrelated to the amount of activity and determined mostly by solute excretion. O'Connor (1975) reported that dogs also drank water at zero to five of six short rest stops when running on a treadmill at 10 km·h^{-1} for 1 hour. With the exception of one dog that did not drink, dogs drank 4-13 mL·kg BW^{-1} during the hour of exercise and did not become dehydrated over time. When no water was offered during the run, dogs always drank if offered water immediately after the run, but did not drink until they were 0.5-1 percent dehydrated if water was offered more than 5 minutes after a run (O'Connor, 1972). Dogs, therefore, drink in anticipation of a need when exercising, but not at rest.

Young et al. (1960, 1962) measured water intake and weight loss in trained 8- to 12-kg young adult beagles at rest and when running for 40 minutes at approximately 50 percent of peak effort (6 km·h^{-1} on a 16-21 percent slope) at an ambient temperature of 18-21°C and 50 percent relative humidity. Dogs drank 547 ± 90 mL at rest while consuming 670 ± 97 kcal (approximately 0.8 mL·kcal^{-1}). Dogs became dehydrated when running even when given free access to water. Dogs consumed only 0.5 mL·kcal^{-1} energy expended during short runs but 1 mL·kcal^{-1} energy expended during long runs. Weight loss due to dehydration relative to energy expended decreased with the length of the run. Urine output was also less for short runs (70 ± 30 mL per 300 kcal) than for long runs (150 ± 104 mL per 1,800 kcal). Young et al. (1959a, 1960) reported that in three separate experiments, provision of 0.94 L (0.56 mL·kcal^{-1}), 1.5 L (0.7 mL·kcal^{-1} ME), and 1.8 L (approximately 1 mL·kcal^{-1}) of water during moderate exercise increased maximum work capacity 70 percent from 980 to 1,696 kcal, 80 percent from 1,191 to 2,141 kcal, and 100 percent from 1,000 to 2,000 kcal, respectively.

When they were not allowed access to water, dogs lost 1.16 ± 0.98 mL·kcal^{-1} ME at normal body weight and 1.84 ± 0.74 mL·kcal^{-1} ME after a 20 percent increase in body weight (Young, 1960). Water requirements, therefore, increased 50 percent in obese animals. Young (1959) also reported that water loss decreased from 1.28 ± 0.34 within 24 hours of eating to 0.94 ± 0.34 mL·kcal^{-1} after 4 days of food deprivation. Thus, water requirements decreased 25 percent in food-deprived underweight animals. When allowed access to water while undertaking exhaustive exercise, postprandial dogs drank 1.6 ± 0.5 L (0.65 mL·kcal^{-1} ME) while expending a mean of 2,332 kcal, but still lost 7 ± 2 percent BW; after 5 days of food deprivation, dogs drank 3.5 ± 0.6 L (0.87 mL·kcal^{-1} ME) while expending a mean of 4,056 kcal, but

still lost 12 ± 0.1 percent BW. These results suggest that dogs required 1 mL·kcal^{-1} ME before food deprivation and 1.1 mL·kcal^{-1} ME after food deprivation to prevent loss of weight. The food fed to dogs in these experiments was described in only one experiment as containing 24 percent protein, 49 percent carbohydrate, and 7 percent fat (presumably as fed).

Taylor et al. (1958) reported that sled dogs in the Antarctic ate snow because they rarely had an opportunity to drink. In an ambient temperature of –45°C, dogs were estimated to consume 1 kg snow and 20 g water in a food providing approximately 2,500 kcal ME daily (i.e., dogs consumed approximately 0.4 mL·kcal^{-1} ME). Hinchcliff et al. (1998) found that sled dogs lost a mean of 5 percent of body weight when completing the Iditarod Trail Race and dogs that did not finish lost a mean of 9 percent body weight. Hinchcliff et al. (1997c) reported that water turnover in sled dogs in ambient temperatures well below freezing increased dramatically from 1.1 ± 0.6 L·d^{-1} (approximately 111 mL·kg BW$^{-0.75}$·d^{-1}) in sedentary dogs to 5.0 ± 3.6 L·d^{-1} (approximately 430 mL·kg BW$^{-0.75}$·d^{-1}) in dogs running at an average speed of 7 km·h^{-1} for 65 hours. Hinchcliff et al. (1997b) also reported that the energy consumption of sled dogs under these conditions was approximately 263 kcal ME·kg BW$^{-0.75}$·d^{-1} in sedentary dogs and 1,082 kcal ME·kg BW$^{-0.75}$·d^{-1} in running dogs. Water turnover (including metabolic water) was, therefore, approximately 0.42 mL·kcal^{-1} ME in sedentary dogs and 0.40 mL·kcal^{-1} ME in running dogs. These dogs consumed a high-protein diet containing 31 percent ME as protein, 54 percent ME as fat, and 15 percent ME as carbohydrate (Hinchcliff et al., 1997b).

Greyhounds lose little water during a race, but dogs are kept in a pen without access to water for up to 6 hours before a race. Blythe and Hansen (1986) reported that in Oregon during August, dogs lost up to 6 percent BW prior to racing. Most dogs (50 percent) lost less than 1 percent BW prior to racing, 36 percent lost 1-2.4 percent BW, and only 5 percent lost more than 2.4 percent BW. Female dogs and dogs racing in later races were more likely to lose more than 2.4 percent BW than male dogs or dogs racing earlier. Dogs losing more than 2.4 percent BW were more likely to perform well in the first five races, and among dogs losing more than 2.4 percent BW, males performed better than females in the final seven races. McKeever et al. (1985) reported that water intake of untrained greyhounds increased 34 percent from 1 L·d^{-1} (approximately 80 mL·kg BW$^{-0.75}$·d^{-1}) to 1.3 L·d^{-1} (approximately 108 mL·kg BW$^{-0.75}$·d^{-1}) after 14 days of training in which dogs were run on a treadmill at 13 km·h^{-1} on a 4 percent slope (65 percent of maximum work capacity) for 30 minutes daily at a mean ambient temperature of 20°C and relative humidity of 16 percent. This increase was not a result of an increase in solute load because food intake was kept unchanged. The increased water intake was associated with a 27 percent increase in plasma volume and a 21 percent increase in blood volume.

In summary, therefore, dogs should be offered free access to water at rest and before, during, and after exercise to optimize performance and reduce the risk of hyperthermia. Ideally, dogs should be offered water during exercise whenever they lose 0.5 percent of body weight. Requirements increase with exercise almost in parallel to the amount of energy expended, but can more than double in a warm environment. In a very cold environment, sled dogs required an average of approximately 0.4 L per 1,000 kcal ME at rest or during exercise. At an ambient temperature of 20°C, sedentary dogs in kennels require an average of 0.6-1.2 L per 1,000 kcal ME, depending on the salt content of the diet and require an average of 0.6-1.2 L per 1,000 kcal ME during exercise, but obese dogs may require 1.8 L per 1,000 kcal ME during exercise. Dogs should be offered more than twice these average amounts, however, because a few individuals may require twice as much water as the mean.

Sodium, Potassium, and Chloride

Mild hyponatremia without clinical signs has been reported to develop in Alaskan sled dogs during long-distance sled dog races (Hinchcliff et al., 1997a,c). Such small changes in electrolyte concentrations in the blood must be interpreted with caution, however, because they do not necessarily reflect loss of total body electrolytes. Hyponatremia can result from dilution, a response to changes in acid-base status, the timing of a sample relative to the race, and an absolute decline in total body sodium.

Hinchcliff et al. (1997a), however, estimated total exchangeable cation content by multiplying the serum sodium concentration by total body water (estimated as 0.66 times the body weight) in Alaskan sled dogs before and after a 480-km race. During the race, the mean serum sodium concentration declined only 2 percent (from 148 to 145 mmol·L^{-1}) but body weight decreased 2.5 percent (0.6 kg); so, there was a 5 percent decrease in cation content and a 2 percent decrease in cation content relative to body weight. Total body water (measured using deuterium dilution) did not change relative to body weight during the race, but dogs lost 0.6 kg body weight; so, there must have been an absolute loss of body water. Sodium intake was not reported.

Hinchcliff et al. (1998) also found that serum sodium concentrations were less than the reference range in more dogs that did not finish the Iditarod Trail Race (71 percent) than in dogs that finished (58 percent). The mean serum sodium concentration in both groups was only 2 mmol·L^{-1} less than the lower limit of the reference range however, and mean loss of body weight was greater (9 percent vs. 5 percent) in dogs that did not finish than in dogs that finished the race. The sodium content of the diet was not reported.

Small changes in potassium concentration also do not necessarily reflect changes of potassium within cells or an increased requirement for potassium. Gannon (1980) has

suggested that lactic acidosis after a race increases potassium loss in the urine and may cause intracellular potassium deficiency and exertional rhabdomyolysis in greyhounds that are raced too frequently. Knochel et al. (1985) found that training reduced plasma potassium concentrations and reduced the increase in plasma potassium concentration following exercise but increased intracellular potassium, skeletal sarcolemmal sodium:potassium ATPase activity, and muscle membrane potential. Fomin (1930) also found 10-17 percent more potassium in muscles from a leg exercised with an extra load.

Changes in the rate of excretion of electrolytes are of greater consequence. Hinchcliff et al. (1997c) reported that the mean serum sodium concentration declined 6 percent (from 149 to 140 mmol·L^{-1}) in dogs during a 480-km sled dog race despite evidence of renal conservation of sodium. Mean plasma concentrations of aldosterone and renin activity increased threefold, while concentrations of arginine vasopressin decreased 50 percent and concentrations of atrial natriuretic peptide changed little. Urine concentrations of sodium, potassium, and chloride and fractional excretion of sodium and chloride decreased 50-80 percent during the race while water turnover increased fourfold. The authors suggested that solute diuresis associated with the excretion of urea increased urine sodium losses. Urea excretion was increased because dogs consumed 960 g protein (29 percent ME) during the race. Dogs consumed approximately 300 mg·kg BW^{-1} sodium during the race, which is well above the normal daily requirement of sedentary dogs, but the sodium content of the diet relative to ME was very low (71 mg sodium per 1,000 kcal ME).

McKeever et al. (1985) reported that plasma volume increased 27 percent, water intake increased 34 percent, and urine output increased 21 percent in greyhounds at the end of 14 days of moderate-intensity training (20 minutes daily at 13 km·h^{-1} on a 4 percent grade) on a treadmill. Plasma concentrations of sodium did not change with training and plasma potassium concentrations increased slightly (0.8 mmol·L^{-1}), but total plasma sodium and potassium content increased 1.5 g (24 percent) and 0.15 g (48 percent), respectively. Total daily sodium excretion in the urine almost doubled from 1.6 ± 0.7 g to 3.0 ± 1.1 g, whereas total daily urinary excretion of potassium (2.5 ± 1.0 g) did not change with training because sodium clearance increased by 90 percent, but potassium clearance decreased 12 percent. If these dogs were 30-kg greyhounds consuming 155 kcal·kg $BW^{-0.75}$·d^{-1}, this would represent an increase from 0.8 ± 0.3 to 1.5 ± 0.5 g per 1,000 kcal of urinary sodium loss with training while potassium loss in the urine remained unchanged at 1.3 ± 0.5 g per 1,000 kcal ME. These changes were not a result of changes in solute intake as dogs were fed the same amount of food throughout. Dogs in training may, therefore, require an additional 0.7 g per 1,000 kcal ME sodium but no additional potassium. It remains to be determined, however, whether this increase in urinary excretion of sodium and increased sodium requirement is maintained after the initial 2 weeks of training.

Young et al. (1962) also measured urinary excretion of sodium and potassium 17 hours after a meal in trained young adult beagles either at rest or when undertaking 3 hours of aerobic exercise (at approximately 50 percent $\dot{V}O_2$max). The mean rate of excretion of potassium in the urine was three times higher in dogs during exercise than at rest, but the rate of sodium excretion did not change with exercise. Relative to energy expended, however, the rate of urinary excretion of sodium and potassium declined during exercise. Thus, urinary potassium excretion was 0.9 ± 0.8 g per 1,000 kcal ME at rest but only 0.3 ± 0.3 g per 1,000 kcal ME during exercise. Urinary sodium excretion was 1.3 ± 1.4 g per 1,000 kcal ME at rest but only 0.2 ± 0.2 g per 1,000 kcal ME during exercise.

Sodium excretion in urine changes markedly, however, if dogs are deprived of water during exercise. Ramsay and Thrasher (1991) reported that dogs did not concentrate their urine when deprived of water but developed a protective natriuresis (124 ± 9 mg·kg^{-1}·d^{-1}) that reduced the rise in plasma osmolality caused by dehydration but obligated continued excretion of water. When water was once more made available, dogs drank rapidly, replacing the deficit in less than 5 minutes, and a profound sodium retention restored sodium balance. Dehydration during a race will therefore clearly exacerbate sodium losses in the urine, but provision of increased sodium in the diet should not be necessary to combat the natriuresis caused by dehydration.

Water is also lost by vaporization from oral and respiratory epithelium. Young (1960) reported that dogs lost approximately 30 percent of water by salivation during exercise and that this "drip loss" (pH 8.8) contained 217 mg·L^{-1} nitrogen, 1.3 g·L^{-1} sodium, 0.3 g·L^{-1} potassium, 24 mg·L^{-1} magnesium, 92 mg·L^{-1} calcium, and 18 mg·L^{-1} phosphorus. Assuming water losses of approximately 1 mL·$kcal^{-1}$ during exercise, 70 mg nitrogen or 0.4 g crude protein, 0.4 mg sodium, 0.1 mg potassium, 8 µg magnesium, 31 µg calcium, and 6 µg phosphorus would be required for each additional kilocalorie of food consumed above the MER. These amounts are small compared to the minimum requirements of average dogs. Young's experiment was performed at room temperature (approximately 20°C) however, and drip loss of electrolytes may be higher when dogs exercise at higher ambient temperatures.

Blatt et al. (1972) collected fluid secreted at high ambient temperatures by the large serous nasal gland, which opens through a single duct 2 cm inside each nostril in mongrel dogs. There was little secretion below 20°C, but secretion increased to 2.6, 4.6, and 9.6 g·h^{-1} per gland at 30, 40, and 50°C, respectively. Secretions contained 0.4-0.8 g·L^{-1} sodium and 0.7 to 0.8 g·L^{-1} potassium, and were less osmotic than plasma. These electrolytes would be absorbed in the intestine if swallowed but can contribute to salivary drip losses. Salivary drip rate increased above 20°C in these

dogs to 0-4 mL·kg $BW^{-0.75}$·h^{-1} at 40°C and 0-9 mL·kg $BW^{-0.75}$·h^{-1} at 50°C. If the composition of this drip fluid was similar to that during exercise, dogs would also lose up to 216 mL·kg $BW^{-0.75}$ daily in salivary drip losses at 50°C, but this would result in loss of only 47 mg·kg $BW^{-0.75}$ nitrogen, 0.3 g·kg $BW^{-0.75}$ sodium, 0.1 g·kg $BW^{-0.75}$ potassium, 5 mg·kg $BW^{-0.75}$ magnesium, 20 mg·kg $BW^{-0.75}$ calcium, and 4 mg·kg $BW^{-0.75}$ phosphorus. With the exception of sodium, these values are small relative to normal requirements and dogs should not require increased electrolytes in a warm environment. Average dogs may, however, require as much as 1 g per 1,000 kcal ME sodium when the ambient temperature is constantly 40°C and up to twice this amount when the ambient temperature is constantly 50°C. In practice however, ambient temperatures decline at night and even outdoor dogs should require less than half this amount.

Few studies have reported the sodium and electrolyte content of diets fed to exercising dogs. Orr (1966) reported that tethered sled dogs in the Antarctic were fed seal meat containing 0.2-0.4 g per 1,000 kcal ME sodium and chloride and 0.04 to 4 g per 1,000 kcal ME potassium, depending on whether the meat was lean or included fat. These dogs maintained body weight while pulling heavy loads for several weeks over long distances in an ambient temperature of –8°C and consuming diets containing 0.9 g per 1,000 kcal ME sodium and 1.0-1.2 g per 1,000 kcal ME potassium and chloride. These dogs would have consumed approximately 0.24 g·kg $BW^{-0.75}$ sodium and 0.3 g·kg $BW^{-0.75}$ potassium and chloride daily. Hammel et al. (1977) and Kronfeld et al. (1977) measured serum electrolyte changes in sled dogs fed diets containing 1.5-1.6 g per 1,000 kcal ME sodium and 1.9-2.7 g per 1,000 kcal ME potassium. Dogs consumed approximately 0.3-0.7 g·kg $BW^{-0.75}$ sodium and 0.4-1.2 g·kg $BW^{-0.75}$ potassium daily. There was no change in serum sodium concentrations with exercise when dogs ran for 12 miles in less than 40 minutes, but serum sodium increased 10 percent during 24 weeks of training in which dogs ran 800 miles. Serum sodium concentrations declined again after training ended. Changes in serum potassium concentrations were not discussed. Querengaesser et al. (1994) reported no change in serum sodium or potassium concentrations or body weight in sled dogs after a 9-km test run or after 24 weeks of training (over a total 802 km) and sprint racing (over a total 414 m) at an ambient temperature of –4 to +6°C when consuming diets containing 0.4 g per 1,000 kcal ME sodium and 0.6 g per 1,000 kcal ME potassium. Hill et al. (2000, 2001b) reported that serum sodium and potassium concentrations and body weight did not change over time in greyhounds raced more than 500 m twice weekly when consuming diets containing 1.3-1.6 g per 1,000 kcal ME sodium and 1.2-1.4 g per 1,000 kcal ME potassium. These dogs consumed approximately 0.2 g·kg $BW^{-0.75}$ sodium and potassium daily. Together, these studies suggest adequate intakes of sodium, potassium, and chloride of 1 g per 1,000 kcal ME for dogs undertaking more than average amounts of exercise.

Safe Upper Limit

Ladd and Raisz (1949) reported that sedentary 14- to 17-kg mongrel dogs were capable of excreting 4 g sodium·kg BW^{-1} daily for 6 days without showing any sign of salt retention. This is equivalent to approximately 8 g sodium·kg $BW^{-0.75}$·d^{-1} or 66 g per 1,000 kcal ME in a dog consuming 120 kcal·kg $BW^{-0.75}$·d^{-1} or 8 g per 1,000 kcal ME in a sled dog running a long-distance race in the cold. High-sodium diets are not recommended, however, because excretion of very high sodium loads requires increased urinary excretion of water, which may increase the risk of dehydration. High-sodium diets can also affect the requirements for other minerals (see Chapter 7).

Fluids Containing Electrolytes

Holloway et al. (1996) reported that oral administration of sodium bicarbonate (400 mg·kg BW^{-1}) to greyhounds before a 500-m race increased arterial pH, and sodium and bicarbonate concentrations, decreased chloride concentrations, but did not affect lactate concentrations or race times compared to values obtained after oral administration of lactated Ringer's solution. Mazin et al. (2001) reported that serum sodium concentrations fell but performance was subjectively unaffected when search-and-rescue dogs received an electrolyte mixture containing 9 percent protein, 65 percent glucose, 14 percent sodium, and 2 percent potassium during 8 hours of training. Young et al. (1960) reported that a mineral mixture containing 1.6 g·L^{-1} potassium, 0.9 g·L^{-1} phosphorus, 0.5 g·L^{-1} sodium, 0.2 g·L^{-1} magnesium, 0.2 g·L^{-1} copper, and 0.2 g·L^{-1} iron given to exercising dogs free-choice during exercise caused diarrhea.

Ramsay and Thrasher (1991) reported that dehydrated dogs were unable to discriminate the nature of the fluid drunk to replace their deficit. Dehydrated dogs consumed similar amounts of water, saline, mannitol, milk, and soup, but, whereas water returned osmolality to normal and satisfied their thirst completely, dogs continued to drink the other solutions that did not return plasma osmolality to normal. Currently, therefore, electrolyte-containing solutions do not appear to have any benefit over water for maintaining hydration in exercising dogs or dogs in high ambient temperatures.

Calcium, Phosphorus, and Magnesium

Meat is commonly fed to sled dogs and greyhounds but is not a balanced food. Feeding meat without adequate calcium supplementation can result in hyperparathyroidism, poor bone mineralization, and increased risk of fractures in dogs (Morris et al., 1971). Fractures of the tarsus, carpus,

metacarpi, and metatarsi are common in racing greyhounds, and many areas of increased bone remodeling are evident with scintigraphy in the carpi and metacarpi of racing greyhounds, often in the absence of radiographic signs of injury (Bloomberg and Dugger, 1996; Zuber et al., 1996). Bone mineral density also may affect the incidence of fractures in racing sled dogs (Stoliker et al., 1976). Excess calcium supplementation, however, can increase the risk of osteochondritis dissecans (OCD) in growing large-breed dogs (Hazewinkel et al., 1985). This risk is also present in exercising dogs. Slater et al. (1992) reported an increased risk of OCD in dogs that played one or more times daily with other dogs and suggested that OCD may be precipitated by cartilage damage during vigorous exercise. The risk of OCD was increased in dogs consuming increased calcium in the diet. The median calcium intake in dogs with OCD was 3.6 g per 1,000 kcal ME compared to 3.1 g per 1,000 kcal ME in control dogs. Dogs fed specialty dry dog foods were at less risk of OCD, but dogs of different body weights were fed differently in the control and affected animals, so an unrelated factor may have been responsible for this difference.

Bones are 10 percent heavier relative to body mass in exercising dogs than in sedentary dogs (Arokoski et al., 1993), but no studies have compared the calcium requirements of exercising and sedentary dogs. Calcium absorption may be slightly reduced with high-fat foods, but this effect is small. The requirement for calcium relative to body weight is probably not much increased above that of sedentary dogs. The requirement for calcium relative to ME is probably lower, therefore, in dogs undertaking exercise in proportion to the extra energy required above MER for kenneled dogs.

Few studies have reported the calcium, phosphorus, or magnesium content of diets fed to exercising dogs. Orr (1966) reported that tethered sled dogs in the Antarctic were fed seal meat containing less than 0.03 g calcium per 1,000 kcal ME, 0.2 to 1.8 g phosphorus per 1,000 kcal ME, and 0.03-0.2 g magnesium per 1,000 kcal ME, depending on whether the meat was lean or included fat (i.e., the calcium to phosphorus ratio was much less than 1:1). These dogs pulled heavy loads for several weeks over long distances when consuming diets containing 2.1-4.3 g calcium per 1,000 kcal ME, 1.6-2.1 g phosphorus per 1,000 kcal ME, and 0.13-0.16 g magnesium per 1,000 kcal ME (see Table 11-3). Dogs would have consumed approximately 0.6-1.2 g calcium·kg $BW^{-0.75}$, 0.4-0.6 g phosphorus·kg $BW^{-0.75}$, and 0.03-0.04 g magnesium·kg $BW^{-0.75}$ daily.

Hammel et al. (1977) and Kronfeld et al. (1977) measured serum electrolyte changes in sled dogs fed diets containing 3.0-4.3 g calcium per 1,000 kcal ME, 2.3-3.0 g phosphorus per 1,000 kcal ME, and 0.15-0.49 g magnesium per 1,000 kcal ME. Dogs would have consumed approximately 0.7-1.9 g calcium·kg $BW^{-0.75}$, 0.5-1.3 g phosphorus·kg $BW^{-0.75}$, and 0.03-0.21 g magnesium·kg $BW^{-0.75}$ daily. Serum calcium, phosphorus, and magnesium all decreased immediately after exercise when dogs ran for 12 miles in less than 40 minutes. During 24 weeks of training in which dogs ran 800 miles, serum calcium decreased and then increased, but differences in serum calcium concentrations between dogs fed different diets were not proportional to calcium content. Serum phosphorus concentrations declined during training in dogs fed a diet containing less phosphorus but no carbohydrate and increased fat and protein, and increased during training in dogs fed more phosphorus and carbohydrate and less protein and fat in the diet. Serum phosphorus concentrations increased at the end of training in dogs fed the lower-phosphorus diets. This suggests that diets for sled dogs should contain at least 3 g phosphorus per 1,000 kcal ME in the diet. Serum magnesium increased during training and declined at the end of training and was higher in dogs consuming diets containing more magnesium.

Querengaesser et al. (1994) reported no change in serum calcium, phosphorus, or magnesium concentrations in sled dogs after a 9-km test run or after 24 weeks of training when consuming diets containing 2.6 g calcium per 1,000 kcal ME, 1.4 g phosphorus per 1,000 kcal ME, and 0.07-0.11 g magnesium per 1,000 kcal ME. Hill et al. (2000, 2001b) reported that serum calcium, phosphorus, and magnesium concentrations did not change over time in greyhounds raced more than 500 m twice weekly when consuming diets containing 2.3-3.0 g calcium per 1,000 kcal ME, 2.0-2.5 g phosphorus per 1,000 kcal ME, and 0.2-0.3 g magnesium per 1,000 kcal ME. These dogs consumed approximately 0.2 g ·kg $BW^{-0.75}$ sodium and potassium daily. Serum phosphorus concentration declined more after exercise in dogs fed a higher-carbohydrate, lower-fat and protein diet than in dogs fed a lower-carbohydrate, higher-fat and protein diet (Hill et al., 2000), but the phosphorus was only 0.1 g per 1,000 kcal ME lower (2.1 vs. 2.0 g per 1,000 kcal ME) in the higher-carbohydrate diet. It is possible, however, that greyhound diets containing increased carbohydrate may require more than 2.0 g per 1,000 kcal ME phosphorus.

Trace Minerals

Even fewer studies have reported the trace mineral composition of diets fed to exercising dogs. Orr (1966) reported that tethered sled dogs in the Antarctic were fed seal meat containing 0.02 g per 1,000 kcal ME iron, and dogs pulled heavy loads for several weeks over long distances when consuming diets containing 0.01 g per 1,000 kcal ME iron. Dogs would have consumed approximately 27 µg iron·kg $BW^{-0.75}$ daily. Querengaesser et al. (1994) reported feeding sled dogs diets containing 15 mg iron per 1,000 kcal ME, 1.8 mg copper per 1,000 kcal ME, 14-15 mg zinc per 1,000 kcal ME, 0.8 mg manganese per 1,000 kcal ME, and 0.04 mg iodine per 1,000 kcal ME, during and after 24 weeks of training. Hill et al. (2000, 2001b) reported feeding greyhounds raced more than 500 m twice weekly for 16 and 22 weeks diets containing 72-91 mg iron per 1,000 kcal ME, 1.9-5.7 mg copper per 1,000 kcal ME, 16-48 mg zinc per

1,000 kcal ME, 4-11 mg manganese per 1,000 kcal ME, 0.3-0.4 mg iodine per 1,000 kcal ME, and 0.1 mg selenium per 1,000 kcal ME.

Vitamins

Few studies have measured the vitamin requirements of exercising dogs. Requirements for thiamin and probably other vitamins are likely to be proportional to energy intake and will, therefore, be much higher relative to body weight in racing sled dogs than in sedentary dogs. In humans, the requirement for pyridoxine increases with protein intake and exercise (Miller et al., 1985; Manore et al., 1987; Manore and Leklem, 1988; Hansen et al., 1996). Minimal requirements for pyridoxine are likely, therefore, to be greater in sled dogs fed high-protein diets than in sedentary dogs, but no studies in sled dogs have reported pyridoxine concentrations in the diet.

Taylor et al. (1958) reported that male sled dogs weighing on average 41 kg and female sled dogs weighing on average 34 kg and undertaking long-distance journeys in the Antarctic in the middle of the twentieth century were fed 0.45-kg (1-pound) blocks of food daily containing no vitamin A, 0.4 mg thiamin, 1.5 mg riboflavin, 17.8 mg nicotinic acid, and <3 mg vitamin C. These authors reported that thiamin and riboflavin excretion in the urine decreased and bisulfite-binding substances in the urine increased when sled dogs consumed this diet, but bisulfite-binding substances decreased in the urine when 100 mg thiamin was injected intramuscularly. These authors developed a diet containing more fat and less protein in which 1,000 international units (IU) vitamin A, 600 IU vitamin D, 1.2 mg thiamin, 3 mg riboflavin, 9 mg nicotinic acid, 2 mg calcium pantothenate, and 0.4 mg pyridoxine were added to each 0.45-kg (2,400-kcal ME) block. This is equivalent to approximately 125 retinol equivalents (RE) per 1,000 kcal ME of vitamin A, 6 µg per 1,000 kcal ME of vitamin D, 0.5 mg per 1,000 kcal ME of thiamin, 1.2 mg per 1,000 kcal ME of riboflavin, 3.7 mg per 1,000 kcal ME of nicotinic acid, and 0.8 mg of calcium pantothenate per 1,000 kcal ME. Wyatt (1963) reported dogs subjectively performed better on the new diet, but changes in the diet other than vitamin composition could have been responsible for the improvement. Querengaesser et al. (1994) fed sled dogs a diet containing 4,700 RE vitamin A per 1,000 kcal ME and 0.4 µg vitamin D per 1,000 kcal ME without notable changes in health or blood chemistries during 24 weeks of training.

Arnrich et al. (1956) reported that some Cocker spaniel puppies fed diets deficient in riboflavin or pantothenic acid collapsed in a hypoglycemic coma after swimming for 25 minutes in 25°C water. In dogs fed a balanced purified diet containing 18 percent ME as protein and 61 percent ME as carbohydrate, 0.46 mg riboflavin per 1,000 kcal, and 14 mg calcium pantothenate per 1,000 kcal, blood glucose increased 34 $mg \cdot dL^{-1}$ immediately after exercise, decreased to 6 $mg \cdot dL^{-1}$ below normal 1 hour after exercise, and then rebounded to normal 2 hours after exercise. In riboflavin-deficient dogs, the increase in blood glucose concentrations immediately after exercise was much greater (73 $mg \cdot dL^{-1}$ above normal), and in both pantothenic acid-deficient and riboflavin-deficient dogs, blood glucose concentrations decreased more (to 14 and 19 $mg \cdot dL^{-1}$ below normal, respectively) and stayed low 1-2 hours after exercise. Some of these deficient dogs collapsed and died with blood glucose concentrations between 14 and 44 $mg \cdot dL^{-1}$. Normal growth resumed when deficient dogs were fed the balanced diet, but glycemic responses to exercise did not return to normal for 3 weeks.

The amount of each vitamin in these "balanced" diets is less than or only slightly more than the amount recommended for maintenance in Chapter 8. At present therefore, there seems to be no reason to increase the minimum recommendations relative to energy intake for vitamins in diets of exercising dogs.

Creatine

Creatine as creatine phosphate acts as an energy buffer in muscle cells, moderating changes in ATP concentration. During muscle contraction when ATP becomes depleted, creatine kinase hydrolyzes creatine phosphate to creatine, and the high-energy phosphate is transferred to ADP to replenish ATP. Creatine is then usually rapidly rephosphorylated, but some creatine is continuously dehydrated to creatinine and excreted in the urine. Snow et al. (1987) reported that 10 percent of creatine phosphate was hydrolyzed to creatine in trained racing greyhounds during a 400-m sprint.

If creatine phosphate becomes depleted during intense exercise however, transfer of a high-energy phosphate from one ADP molecule to another ADP molecule generates additional ATP but also generates adenosine monophosphate (AMP). This AMP is then broken down to ammonia, hypoxanthine, and uric acid by xanthine oxidase, generating reactive oxygen species (ROS) (Sahlin et al., 1991). By preventing the generation of AMP from ADP, creatine phosphate can, therefore, also limit the production of ROS.

Creatine is not considered an essential nutrient in mammals because it can be synthesized in the kidney and liver from glycine, arginine, and *S*-adenosylmethionine. Nevertheless, creatine can be absorbed orally, and oral creatine supplementation increased muscle concentrations of creatine in humans with low resting muscle concentrations of creatine, but did not affect muscle concentrations in humans with high resting muscle concentrations of creatine (Balsom et al., 1994). Supplemental creatine has also improved performance and recovery in humans undertaking short-duration, repetitive, high-intensity exercise (Balsom et al., 1994).

In dogs, Benedict and Osterberg (1923) demonstrated that oral creatine was absorbed and excreted in the urine. All

creatine was retained in the body for the first few days but subsequently appeared in the urine as creatine and creatinine. Body weight increased in these creatine-supplemented dogs. Body weight has also been reported to increase in humans supplemented with creatine (Balsom et al., 1994). Harris and Lowe (1995) and Lowe et al. (1998) have shown that plasma creatine concentrations increased markedly for at least 4 hours after dogs were supplemented orally with up to 3 mmol·kg BW^{-1} synthetic creatine or 2 g creatine in raw meat. Nevertheless, creatine is degraded to creatinine by heat processing, and pet dogs and cats fed heat-processed commercial petfood must consume very little creatine. Harris et al. (1997) showed that uncooked chicken, beef, and rabbit meat contained 30 mmol·kg^{-1} wet weight of creatine; ox heart and liver contained 22 and 2 mmol·kg^{-1} wet weight, respectively; and dried meat contained 90-100 mmol·kg^{-1} DM of creatine, but that heat-processed canned and dry commercial petfoods and dried rendered meat meal contained less than 4 mmol·kg^{-1} DM of creatine. Lowe et al. (1998) reported that oral supplementation with up to 3 mmol·kg BW^{-1} creatine daily for 4 weeks did not increase mean total creatine concentrations in the muscle of caged beagles previously fed a commercial diet containing less than 0.2 mmol·kg^{-1} creatine. Muscle creatine concentrations appeared to increase over time in those dogs with low initial muscle concentrations of creatine, but there were no unsupplemented control dogs for comparison. Scott et al. (1999) found no evidence of an effect of creatine supplementation on either total muscle creatine concentrations or running speed of trained racing greyhounds compared to unsupplemented controls when dogs were supplemented with 2.5 g creatine three times daily for 6 weeks. Clark et al. (1988), however, have shown that the reduction in phosphocreatine during muscle contraction is much less in canine muscle that has previously been conditioned by repetitive electrical stimulation. Currently, therefore, there is no evidence for any benefit from adding creatine to the diet of exercising dogs, and any such effect is likely to be small compared to the benefit observed after conditioning.

Creatine Kinase

Creatine kinase is the enzyme that catalyzes the interconversion of creatine and creatine phosphate. This enzyme leaks into the serum of normal animals. The rate of this leak and the serum concentrations increase in proportion to muscle damage, and very high serum concentrations may be associated with exertional rhabdomyolysis (Aktas et al., 1993). In trained racing greyhounds, mean serum creatine kinase concentrations at rest were unaffected by repeated racing during a racing season, but mean concentrations increased up to twofold (approximately 200 U·L^{-1}) immediately after a sprint race of up to 700 m irrespective of distance raced, and increased to approximately 400 U·L^{-1} 3 hours after a 700-m race (Lassen et al., 1986; Snow et al., 1988; Ilkiw et al., 1989; Nold et al., 1991; Bjotvedt et al., 1993; Hill et al., 2000, 2001b). Similar or smaller increases in serum creatine kinase concentrations were also noted in Labrador retrievers immediately after 10 minutes of intense retrieving exercise, and in sled dogs immediately after runs of up to 9 km (Ready and Morgan, 1984; Querrengaesser et al., 1994; Matwichuk et al., 1999). Serum creatine kinase concentrations increased more in unfit dogs than in fit dogs after an hour of moderate exercise (Sneddon et al., 1989) and increased to more than 1,000 U·L^{-1} in some greyhounds after racing (Lassen et al., 1986; Hill et al., 2000).

Hinchcliff et al. (1993) reported that mean serum creatine kinase concentration was 400 U·L^{-1} or less in most racing sled dogs within 1 hour of their competing in the Yukon Quest International Sled Dog race, but the concentrations increased to 3,000 U·L^{-1} in individual dogs. There was no evidence of a difference in serum creatine kinase concentrations between dogs that did and did not finish the race (Hinchcliff et al., 1996). In dogs withdrawn from the Iditarod Trail Race, however, Piercy et al. (2001b) reported that the median and maximal serum creatine kinase concentrations were much higher (5,100 and 440,000 U·L^{-1}, respectively). Hinchcliff et al. (1998) also reported that the mean and maximal serum creatine kinase concentrations were much higher (2,000 and 57,000 U·L^{-1}, respectively) in dogs that did not finish the Iditarod than in dogs that did finish (640 and 3,000 U·L^{-1}, respectively). Serum creatine kinase concentrations were higher (up to 57,000 U·L^{-1}) in dogs retiring during the first 800 km of the race than in dogs retiring during the final 1,000 km (up to 3,400 U·L^{-1}). These results suggest that serum concentrations of up to 3,400 U·L^{-1} may be normal in dogs undertaking intense exercise but that higher concentrations suggest abnormal amounts of muscle damage.

Antioxidants, Exercise, and Training

Free radicals and ROS are produced during normal metabolism and have the potential to damage protein, fat, and nucleic acids. They are prevented from doing so by antioxidants and antioxidant enzyme systems within the body. Oxidation produces molecules, such as isoprostanes, thiobarbituric acid reducing substances (TBARS), lipid hydroperoxides, and 7,8- dihydro-8-oxo-2' -deoxyguanosine, that can be measured in blood or urine. During exercise, production of ROS and oxidation products increases and concentration of antioxidants in blood decreases. Hinchcliff et al. (2000) reported that plasma isoprostane concentrations increased sevenfold and plasma vitamin E concentrations declined 25 percent in sled dogs that pulled an unladen sled and musher 58 km daily over snow for 3 days. The mean serum creatine kinase concentration also increased moderately (tenfold to approximately 1,000 U·L^{-1}), and this increase correlated with the increase in isoprostane concentration. Hill et al. (1999a) reported that concentrations of

TBARS increased 30 percent and total antioxidant concentrations decreased 10 percent in the blood of trained greyhounds immediately after a 500-m race. Declining antioxidant concentrations in the face of increased concentrations of oxidation products suggests that exercise increases oxidative stress. It remains to be determined, however, whether this oxidative stress causes any pathology in exercising dogs or whether increased supplementation of antioxidant nutrients, such as vitamins E or C, can prevent any oxidative damage caused by exercise.

Training has also been shown to have an effect on both the production of ROS and the antioxidant defense system in exercising dogs. Marin et al. (1993) reported that running 40 km on 26 percent slope at 7 $km \cdot h^{-1}$ decreased total plasma glutathione concentrations 20 percent but did not affect plasma oxidized glutathione concentrations in beagles. These authors found that 30 weeks of training (running for 64 km daily on a 26 percent slope) increased total glutathione concentrations but did not affect oxidized glutathione concentrations in the lung, gastrocnemius muscle, or plasma. This training increased the enzymes responsible for glutathione synthesis two- to threefold in the leg muscles of beagles but did not affect these enzymes in axial muscles or in the liver. Fink (2001) reported that ROS formation increased 80 percent in untrained dogs but did not increase in trained dogs running at 15 $km \cdot h^{-1}$ on a 5 percent slope. The increase in ROS formation in untrained dogs was prevented by infusion of pyruvate. These studies suggest that any benefit from providing additional antioxidants may be greater in untrained than in trained animals.

Vitamin E and Antioxidant Cocktails in Exercising Dogs

Vitamin E is an antioxidant that is an essential nutrient in dogs. Muscular, neuronal, and testicular degeneration, intestinal lipofuscinosis, reproductive failure, and increased fragility of red cells have been reported in sedentary dogs fed vitamin E-deficient diets (Anderson et al., 1939; Brinkhous and Warner, 1941; Elvehjem et al., 1944; Kaspar and Lombard, 1963; Hayes et al., 1970a,b). Retinal degeneration developed in hunting dogs fed a diet of meat and fat deficient in vitamin E but not in hunting dogs fed a commercial diet containing vitamin E (Davidson et al., 1998). Hayes et al. (1970b) reported that plasma tocopherol concentration in normal dogs was more than 5.5 $mg \cdot L^{-1}$, whereas the mean plasma tocopherol concentration in deficient dogs was 2.7 $mg \cdot L^{-1}$.

In normal, trained racing greyhounds, Snow and Frigg (1990) reported that mean plasma tocopherol concentration was 10 $mg \cdot L^{-1}$. Scott et al. (2001) reported that mean plasma tocopherol concentrations decreased from 12 to 7 $mg \cdot L^{-1}$ during a 500-m race in racing greyhounds fed a diet deficient in vitamin E, but that dogs did not exhibit signs of deficiency. Resting concentrations increased to 27 $mg \cdot L^{-1}$ and did not decline during a race when dogs were supplemented with 0.5 g (680 IU) of D-α-tocopheryl acetate daily for 1 week. Hill et al. (2001a) also reported that supplementation of trained racing greyhounds with either 100 or 1,000 IU of α-tocopheryl acetate daily for 8 weeks increased plasma concentrations of tocopherol markedly, but that dogs ran slower than unsupplemented controls when given 1,000 IU daily. Greyhounds weigh 25-30 kg. This suggests that racing greyhounds should receive less than 30 $IU \cdot kg\ BW^{-1}$ vitamin E daily, and supplementation with 3.5 $IU \cdot kg\ BW^{-1}$ vitamin E daily does not have a demonstrably beneficial or detrimental effect.

In trained, racing sled dogs (mean 23 kg BW), Piercy et al. (2000) reported that mean resting plasma tocopherol concentrations were greater (75 vs. 44 $mg \cdot L^{-1}$) in dogs supplemented with 457 IU α-tocopheryl acetate daily (in combination with 706 mg vitamin C and 5.1 mg α-carotene) for 3 weeks compared to unsupplemented controls and that concentrations decreased slightly after exercise (pulling an unladen sled and a musher at 17 $km \cdot h^{-1}$ for 77 km daily for 3 days) in the supplemented dogs. Mean serum creatine kinase concentrations increased to more than 1,000 $IU \cdot L^{-1}$ when dogs were exercised, but this increase was not attenuated by antioxidant supplementation. Antioxidants did not, therefore, prevent any muscle damage associated with exercise in this study. Baskin et al. (2000) also reported that supplementing trained racing sled dogs (mean 21 kg BW) with 400 IU of α-tocopheryl acetate (combined with 3 mg β-carotene and 20 mg lutein orally) for 1 month increased the mean plasma tocopherol concentration from 17 to 30 $mg \cdot L^{-1}$ and increased both plasma lutein and β-carotene concentrations. In this experiment however, plasma concentrations of the oxidation product 7,8-dihydro-8-oxo-2′-deoxyguanosine decreased approximately 20 percent in supplemented dogs but increased approximately 10 percent in unsupplemented dogs after 3 days of exercise (64-75 km daily pulling a lightly laden sled and musher at 19 $km \cdot h^{-1}$). Supplementation did not affect other oxidation products (lipid hydroperoxide concentrations) or the in vitro oxidation rate of lipoproteins. The total antioxidant given to these dogs each day cannot be determined because the antioxidant composition of the base diet was not reported. Nevertheless, no detrimental effects, were reported, which suggests that daily supplementation with 20 $IU \cdot kg\ BW^{-1}$ vitamin E, 30 $mg \cdot kg\ BW^{-1}$ vitamin C, 200 $\mu g \cdot kg\ BW^{-1}$ β-carotene, and 1 $mg \cdot kg\ BW^{-1}$ lutein for 4 weeks may represent a safe upper limit for racing sled dogs.

Piercy et al. (2001a) reported that sled dogs running for up to 1,865 km in the Iditarod Trail Race were twice as likely to finish, and two times less likely to be withdrawn for each kilometer run if their plasma vitamin E concentrations were greater than 41 $mg \cdot L^{-1}$ before racing compared to dogs with concentrations less than 41 $mg \cdot L^{-1}$ before racing. Team speed was not associated with vitamin E concentrations before racing. Among dogs that were withdrawn from the Iditarod Trail Race however, Piercy et al. (2001b) reported that

there was no difference in pre-race vitamin E concentrations between dogs with plasma concentrations of creatine kinase greater than 10,000 IU·L^{-1} (with probable exertional rhabdomyolysis) when they were withdrawn compared to those with concentrations less than 10,000 IU·L^{-1} when they were withdrawn. Dogs that were withdrawn with creatine kinase concentrations greater than 10,000 IU·L^{-1} had lower total antioxidant concentrations when withdrawn but started the race with higher total antioxidant concentrations than dogs with lower creatine kinase concentrations when withdrawn.

Currently, there is no evidence that supplementation of exercising dogs with additional vitamin E or any other antioxidant combination above that suggested for sedentary dogs is necessary to prevent oxidative damage associated with exercise. It is essential, however, to provide adequate vitamin E in the diet. Sled dogs and greyhounds are often fed meat or fish, and sled dogs are often fed very high-fat diets. If this meat is stored for long periods, the fat may become oxidized. Fish also contains polyunsaturated fats. Hayes et al. (1970a) showed that increased consumption of polyunsaturated fats exacerbated changes associated with vitamin E deficiency in sedentary dogs. Creatine kinase concentrations increased, whereas hemoglobin concentrations and hematocrit decreased in proportion to fat consumption. Wander et al. (1997) found that plasma tocopherol concentrations also decreased 20 percent and TBARS concentrations in blood and urine increased in sedentary old beagles fed a diet containing increased amounts of n-3 fatty acids (from fish oil) relative to n-6 fatty acids (a ratio of 1:1 compared to a ratio of 5:1 or higher). The amount of vitamin E provided in the diet of exercising dogs should therefore take into account the amount and type of fat.

Vitamin C

Vitamin C is synthesized in adequate quantities for normal function by sedentary dogs and cats. Plasma ascorbic acid concentrations of up to 19 mg·L^{-1} have been reported in unsupplemented sedentary dogs (Zannoni et al., 1974; Crilly et al., 1976; Robinson et al., 1979; Schwartz, 1980; Lee et al., 1986; Kronfeld et al., 1989). Taylor et al. (1958) reported that sled dogs consuming seal meat excreted 100 mg ascorbic acid daily in their urine and that dogs consuming less than 10 mg ascorbic acid daily, even those with marked palatal ulcers, excreted more than 50 mg daily. These authors concluded that the sled dogs were synthesizing at least 50 mg ascorbic acid daily and did not require an additional dietary supply.

Nevertheless, the rate at which vitamin C is synthesized in the liver is lower in dogs and cats than in other species (Chatterjee et al., 1975). Kronfeld and Donoghue (1988) have suggested that stress or intense exercise may increase the requirement for vitamin C above the synthetic capacity of the liver. Butson (1973) reported that signs of scurvy in sled dogs fed stored frozen meat for long periods were prevented by feeding fresh meat but did not demonstrate that vitamin C was deficient. Donoghue et al. (1993) reported that the mean plasma concentration in trained sled dogs before the racing season was 5.3 mg·L^{-1} in unsupplemented dogs but increased 30 percent to 6.9 mg·L^{-1} in dogs supplemented with 0.5 g vitamin C daily. A day after a major race at the end of the racing season, the mean concentration of vitamin C had decreased in these same dogs, to 2.5 mg·L^{-1} in unsupplemented dogs and 3.7 mg·L^{-1} in dogs receiving 1 g vitamin C daily. After a period of 4 weeks during which these same dogs had not undertaken any activity, the mean concentration increased to 6.6 mg·L^{-1} in unsupplemented dogs and 9.6 mg·L^{-1} in dogs receiving 1 g vitamin C daily. Low plasma concentrations of vitamin C and an increase in these concentrations in response to supplementation do not, however, indicate a deficiency. Piercy et al. (2000), by contrast, reported that mean plasma vitamin C concentrations were 19.1 mg·L^{-1} in unsupplemented sled dogs and 21 mg·L^{-1} in dogs supplemented with 706 mg vitamin C daily (in combination with vitamin E and β-carotene), but vitamin C concentrations increased 25 percent after endurance exercise. The vitamin C content of the base diet was not reported.

In trained racing greyhounds, Snow and Frigg (1990) reported that the mean plasma ascorbic concentration was 5.3 mg·L^{-1}. Scott et al. (2002) reported that the plasma ascorbic acid concentrations were only 1.8-2.8 mg·L^{-1} in trained racing greyhounds receiving little (0.1 mg·kg BW^{-1}) ascorbic acid in their diet. Concentrations doubled after oral administration of 1 g of vitamin C, but returned to normal levels within 6 hours. Schwartz (1980) reported that addition of 1 g of vitamin C daily to the diet increased mean plasma concentrations of vitamin C from 10.5 to 15.4 mg·dL^{-1} and increased mean cartilage weight in beagles with surgically induced osteoarthritis. High doses, however, may not be beneficial. Marshall et al. (2002) found that trained racing greyhounds ran, on average, 0.3 km·h^{-1} slower over 500 m when supplemented daily for 4 weeks with a high dose (1 g) of vitamin C either before or after racing. Although this difference was small, it is equivalent to a lead of 3 m at the finish of a 500-m race. Others have also reported that vitamin C may have a deleterious effect at high doses by acting as a prooxidant in humans (Podmore et al., 1998; Childs et al., 2001). Currently, therefore, supplementation with vitamin C in normal animals is not recommended.

Other Nutrients

Several food additives, including dimethylglycine, pangamic acid (vitamin B_{15}), L-carnitine, inosine, coenzyme Q, bee pollen, methylsulfonylmethane, caffeine, alcohol, and vinegar, have been suggested to improve the performance of racing dogs (Williams, 1992). To date, no controlled studies have shown any benefit in dogs or cats. Gannon and Kendall (1982) reported that dimethylglycine

and diisopropylammonium dichloroacetic acid reduced the race time of greyhounds. Pangamic acid is a substance of uncertain composition. It consists of an ester of dimethylglycine and gluconic acid but may include diisopropylammonium dichloroacetic acid (Herbert, 1988). The beneficial effects described by Gannon and Kendall can probably be ascribed to dichloroacetic acid. Dichloroacetic acid is a potent drug that activates pyruvate dehydrogenase and reduces lactic acidosis (Merrill et al., 1980). The appropriate dose of dichloroacetic acid is uncertain, and neurologic, hepatic, testicular, pulmonary, and pancreatitic toxicity has been described in dogs (Cicmanec et al., 1991).

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12

Diet Formulation and Feed Processing

PETFOOD PROCESSING

Although there are substantial differences in the nutrient requirements of dogs and cats, there are many similarities in the techniques used to manufacture their foods. For this reason, petfood processing is discussed in a generic manner and, when appropriate, issues concerning individual species are addressed separately.

General Considerations

Dogs and cats have a demonstrated requirement for specific nutrients but not a requirement for specific feedstuffs to be included in their diet (AAFCO, 2002). Nevertheless, pets can be quite individualistic in their feeding habits and often exhibit food preferences that may have been conditioned by previous dietary experiences. The conditioned responses may favor a particular form (dry, semi-moist, canned) or texture (mixed; soft-moist; dry; flavor induced by specific ingredients, e.g., fish). It is sometimes difficult to change a pet's feeding behavior, even though the new feed may be nutritionally adequate. A conditioned diet preference should not be confused with nutritional requirements.

Dogs

Dogs differ from cats in that they are not strict carnivores but fall more in the omnivorous category. This fact allows a great deal more latitude in ingredient selection and formulation. It is entirely feasible to formulate an adequate dog diet using no animal tissue-based ingredients. This fact and the remarkable adaptability of the dog have led to the successful use of commercial diets that differ widely in their ingredient composition, texture, and form.

Cats

While cats are true carnivores in the wild, most commercial diets for domestic cats contain significant amounts of vegetable matter that is satisfactorily used by the animal as a nutrient source. However, acceptable commercial cat diets contain a portion of animal source ingredients to meet specific nutrient requirements (e.g., arachidonic acid, taurine) if not met by synthetic sources. Animal tissue-based ingredients also contribute significantly to the acceptability of the food by the cat and, therefore, play a role in adequate consumption. Generally speaking, strict vegetarian diets, when fed alone, are not nutritionally adequate for cats, even though such diets can be made sufficiently palatable to be readily consumed.

PETFOOD CATEGORIES

Petfood generally falls into two broad categories: dry or canned. Dry petfood can be further subdivided into dry-expanded, semi-moist, or soft-expanded, depending on moisture content.

Dry Petfoods

Dry-Expanded

Dry-expanded petfoods typically contain 10-12 percent final moisture content and are formulated using cereal grains, cereal grain by-products, soybean products, animal by-products (including milk by-products), fats and oils, vitamins, and micro- and macrominerals. Whereas dry dog foods may be marketed as meal, pellets, kibbles, extruded, or baked products, dry cat foods are usually processed by extrusion cooking. Because cats lack the molar teeth found in dogs, food particles must be produced in a size and shape suitable for incising rather than grinding by attrition. Extrusion processing is particularly suited for accomplishing this (Rokey and Huber, 1994).

The vast majority of dry petfood marketed is extrusion processed. The extrusion process typically results in moderate to high levels of gelatinization of dietary starch (Mercier

and Feillit, 1975). By gelatinizing part or most of the starch, the site of starch hydrolysis (digestion) occurs in the upper gut, resulting in better utilization by the animal and reduced digestive upset.

Typical modern extrusion systems incorporate a means of conditioning the pre-extrusion mash with both steam and water. After conditioning, the mash is directed into the extruder barrel where additional steam, water, and, in some cases, a meat slurry may be incorporated into the mash. Within the extruder barrel, the material is "cooked" by a combination of friction, shear, and indirect heat to the point that the starch is mostly gelatinized and the heat-labile microbial population is reduced to nil (Rokey and Huber, 1994).

The die, located at the discharge of the extruder, serves two functions in petfood processing. First, it provides a resistive force for the extruder screw and barrel to work against to elevate both frictional heat and pressure resulting in thermal reactions within the extrudate. Second, the die, in combination with the cutter knife, provides the three-dimensional shapes of the petfood.

At the die exit, the mash, now a viscoamorphic mass, will expand upon reaching atmospheric pressure. The expanded, intricately shaped food particles have become very important in satisfying the anthropomorphic desires of contemporary pet owners. Using extrusion processing, a petfood manufacturer can produce a nearly infinite array of shapes, sizes, and colors. This capability is critical in market development but has little to do with the nutritional adequacy of the petfood.

After extrusion processing, the injected steam and water used in the process must be removed by drying. Typical moisture levels reached during processing range from 22 to 28 percent and must be reduced to the range of 10-12 percent for suitable shelf life. Drying is typically accomplished using some form of a continuous dryer with a separate cooler or dryer-cooler combination.

Dry dog and cat foods typically contain 5-12.5 percent crude fat, with the majority of the fat being applied post-processing. These fat levels are achieved by spraying a portion of the liquefied fat onto the extruded product. Additionally, it is common to spray-coat the petfood with various protein digests and/or flavors to increase its acceptance by the pet (Corbin, 2000).

Alternative Food Forms—Meal, Pellets, and Kibbles

As alternate feed forms, meal, pelleted, and kibbled petfoods represent a minor part of the petfood industry. However, some pet owners prefer one of these forms, and they often provide a lower-cost alternative to extruded dry foods.

Meal

Meal form petfoods are a relatively simple mixture of dry ingredients together with fats or oils and, perhaps, a flavoring agent. The official definition of meal (AAFCO, 2002), "an ingredient which has been ground or otherwise reduced in particle size," does not really apply to this feed form. Meal petfoods are more accurately described as "textured" feeds since they are often a blend of heat-processed grain (flaked or extruded) and a pelleted protein supplement that also contains vitamins, minerals, trace minerals, amino acids, and the like. After the grain and pellets are blended, tallow, oils, and/or flavors are applied.

Pelleted Food

As the name implies, the food is in the form of a pellet and is made using conventional feed processing technology. As a rule, the grain in a pelleted diet is heat processed to improve starch availability because the steam conditioning process prior to pelleting is not sufficient to result in significant starch gelatinization. The dry ingredients are weighed, uniformly mixed, steam conditioned, pelleted, cooled, and then coated with tallow, oils, and/or flavors prior to packaging.

Kibbled

Kibbled petfood is processed in a manner similar to baked products, but instead of the dough being formed into distinct shapes, it is simply sheeted and baked (Case et al., 2000). The baked sheets are then broken into small pieces, sieved to remove fines, and packaged. Kibbles are often blended with raw or cooked meat to constitute the pet's ration but, if properly formulated, can be a complete and balanced diet.

Semi-moist Petfoods

Semi-moist petfoods typically have an intermediate moisture level of 25-35 percent. These products are usually cooked through an extrusion process that is very similar to the process used for dry-expanded petfood. There are distinct differences, however, due in large part to the differences in formulations necessary to result in semi-moist products (Rokey and Huber, 1994).

These products contain moisture levels substantially higher than those found in dry-expanded petfoods. Shelf-life stability is obtained by controlling water activity (a_w). Water activity is defined as the measure (amount) of free moisture in a product and is the ratio of the water vapor pressure of the food to that of pure water at the same temperature (Beuchat, 1981; Montville, 1987; Kuntz, 1992). As suggested by this definition, water in association with other substances does not behave like pure water, and one measure of this difference is activity, which may be expressed as a ratio. Through the use of certain ingredients in the formula, generally known as "humectants," water activity can be predicted, and thus, controlled (Rokey and Huber, 1994).

Semi-moist products often contain many of the same basic ingredients as dry-expanded products. However, they usually contain meat or meat by-product slurries incorporated prior to or during extrusion. The ratio of dry to wet ingredients can vary considerably, but generally ranges from 4:1 (dry vs. wet) to 1:1. In addition to the wet slurry, semi-moist petfoods incorporate a combination of water-soluble solids such as sugar, sodium chloride, sorbate, and low-molecular-weight alcohols (e.g., propylene glycol) sufficient to bind a large portion of the water and reduce the product's a_w to an acceptable range (<0.60) for shelf stability. It must be noted that propylene glycol is considered "generally recognized as safe" (GRAS) for use in human food products, dog food, and other animal feed provided specified conditions are met. Federal regulations prohibit the use of propylene glycol in cat food formulations at this time (21 CFR 589.1001).

Semi-moist cat foods commonly contain fresh or frozen meats (e.g., liver, kidney, tripe), animal by-product meal (e.g., meat, poultry, liver), whole or dehulled cereal grains (e.g., corn, wheat, rice), marine products (e.g., fish meal, condensed fish solubles), soy products (e.g., soybean meal, soy flour, soy protein concentrate), fats and oils (e.g., animal fat, marine oils), and mineral and vitamin supplements. Because of the final moisture content, nutrient levels are often expressed on a dry matter (DM) basis. Protein normally ranges from 28 to 40 percent (DM) and crude fat from 10 to 15 percent (DM).

Semi-moist dog foods are made from similar ingredients but are often shaped into "patties" of a size convenient for feeding or packaged to simulate meat chunks. In all cases, semi-moist petfoods must be packaged in low-moisture-diffusion packaging to prevent moisture loss and changes in water activity. These foods are commonly marketed in sealed pouches of a size convenient for feeding as a single meal or in a resealable package to control moisture loss.

Soft-Expanded (Soft Dry) Petfoods

A third category of extrusion processed petfood consists of soft-expanded petfoods. These products are similar to semi-moist in that they often contain a relatively high level of meat by-products and often have higher levels of fats and oils than dry-expanded foods. They differ from semi-moist with respect to taking on an expanded appearance after extrusion (Rokey and Huber, 1994).

With soft-expanded products, the basic extrusion parameters are similar to dry-expanded food processing. However, the ingredients used are more like those found in semi-moist foods and include humectants to control water activity. Typical moisture content of soft-expanded petfoods is in the range of 27-32 percent. Soft-expanded foods are often mixed with dry-expanded and semi-moist foods to produce a highly palatable food with a texture that is appealing to the pet owner.

Baked Petfoods

Although it is not common, some owners of dogs, in particular, prefer to feed baked petfoods rather than a meal, pelleted, or extruded food. These products are usually given the shape of bones or some other stylized shape to attract buyers. Baked petfoods are produced using a traditional means of dough formation, shape cutting or stamping, and oven baking. Because of the nature of the process, formulas commonly contain high levels of cereal flours (>50 percent) and have limited capacity to incorporate wet meat by-products or slurries. The baked food morsels are cooled, screened, and packaged. Fats and oils are seldom applied post-baking, and as a result, these products usually contain 3 to 6 percent crude fat.

Starch-Lipid Complexes

One problem associated with the extrusion process used to produce dog and cat foods of various types is the creation of starch-lipid complexes. These structures were first reported by Charbonnier et al. (1973) and have been identified as an amylose-lipid complex (Asp and Bjorck, 2000). While these complexes do not significantly affect the availability of either starch or lipid to the target animal to any great extent, they do interfere with the assay for ether extract (crude fat). For an accurate crude fat determination one must use an acid hydrolysis procedure.

Snacks for Pets

Historically, pet snacks or treats have been produced using traditional means of processing, which would include dough forming, shape cutting, and oven baking. Snacks of this type are often formed to appear as bones, fish, chicken legs, and the like. In recent years, many pet snacks have been developed using extrusion techniques to form either a dry product or a semi-moist product (Rokey and Huber, 1994). A typical petfoods snack extrusion system would utilize the same equipment and processing principles found in large-scale petfood production facilities.

Because pet snacks are typically marketed in small packages and because issues such as palatability and appearance are highly important, process control and design are more critical than in large-scale facilities. However, pet snacks are gaining in popularity each year and may represent a significant opportunity for some companies.

As a rule, pet snacks do not represent a significant portion of a typical diet for most dogs or cats; however, careful attention to nutrient formulation is necessary. There are no differences in labeling requirements between pet snacks and major food categories for dogs and cats. Dog and cat food products conspicuously identified as a "snack" or "treat" do not have to bear a statement attesting to nutritional adequacy (or lack thereof) as mandated for most other petfoods under Associa-

tion of Animal Feed Control Officials (AAFCO) Model Pet Food Regulations. Also, there is no requirement for snacks or treats to bear feeding directions if the product is not represented as being "complete and balanced" (AAFCO, 2002).

Canned (Wet) Petfoods

The market for canned dog food appears to be level or shrinking, while canned foods for cats enjoy a sizable market share, with annual consumption increasing. Many of the same ingredients utilized in canned petfoods are also used in dry-expanded and semi-moist petfoods although not at the same level. Because canned petfoods are high in moisture (usually 74-78 percent), they often contain much higher levels of fresh or frozen meat, poultry, or fish products and animal by-products. A meat-based formula may contain from 25 to 75 percent meat and/or meat by-products. Many canned petfoods may contain a significant level of textured protein (either soy- or wheat gluten-based) that is essentially a meat analogue with a structure that mimics the appearance of meat. These products have all but replaced earlier fortified "all-meat" formulas because of reduced formula costs and, more importantly, the improved nutrient profiles possible with meat-textured protein combinations.

Higher energy densities in canned petfoods dictate high concentrations of amino acids (protein), vitamins, and minerals. Although these petfoods are designed to be fed alone as a complete and balanced diet, they are commonly used as supplements to improve the acceptability of dry petfoods. Although the addition of canned petfoods, milk, eggs, meat, or broths to dry petfoods may improve acceptability, the nutritional value of a well-balanced dry petfood may not be enhanced.

Canned Petfood Processing

Canned petfood processing is a rather complex endeavor. Typically, the meat and fat ingredients are blended with some amount of water and then appropriate amounts of dry ingredients, such as vitamins, minerals, amino acids, and the like, are added. These ingredients are then blended, and, if the petfood is to have a fine texture, the blend is finely ground to produce a very thick slurry. The mixture may be heated (blanched) to begin the cooking process, or it may be added directly to the can through a filling device. After filling, the cans are sealed with a double-seam lid and retorted. The retort process is essentially a heat and pressure-cooking and sterilization process that ensures destruction of foodborne pathogens.

After retorting, the canned petfood is cooled and dried, and a paper label and production code are applied. The processing involved results in a product that has an extremely long-term shelf life.

Not all canned petfoods are in "cans" per se. Technology now exists to retort products in flexible pouches and other novel containers. For this reason, this category may also be referred to as "wet" petfoods, although all undergo similar processing.

Because of the heat and pressure involved during canning, there is likely some destruction of critical nutrients. For example, thiamin is readily destroyed by heat, especially under neutral or alkaline conditions, and extensive losses may occur in canned petfoods during processing and storage (Baggs et al., 1978). In one study, thiamin content was reduced by 74 percent in canned dog food due to retorting and storage for 14 days (Hoffmann-LaRoche, 1981). Reputable petfood manufacturers have conducted extensive research to determine the extent of these losses and have formulated overages of these nutrients to compensate.

The commercial petfoods industry has created a large variety of canned petfood choices and textures including food with chunks of meat or meatlike morsels, shredded, loaves, and chunks with gravy as well as the traditional ground texture. As with texture, available petfoods are produced from all manner of base ingredients, including fish of various species, poultry, beef, and so on. It is common to have the primary meat ingredient identified as part of the label (e.g., chicken, salmon, turkey giblets).

Regulatory Issues in Canning Operations

Many of the ingredients used in canned petfoods are of animal origin and include various poultry, meat, and marine products. Most of these ingredients are used as a source of protein but often contribute a variety of other required nutrients such as minerals, amino acids (especially taurine), vitamins, fatty acids, and energy. As with all petfoods, these ingredients should conform to the definitions promulgated by AAFCO (2002) in its Official Publication. The petfood industry uses fresh, undecomposed animals and marine tissue from many sources. These may be from the rendering industry and include various meat, poultry, and bone meals; meat scraps; and offal from packing house waste. Additionally, products from slaughter such as freshly boned-out animal tissues and organ meats are often utilized in canned petfoods.

From a regulatory standpoint, canned petfoods are included in the low-acid canned food regulations (LACFRs) found in 21 CFR 113 and 110, and are applied in the same manner as for human low-acid canned food products. When properly processed in accordance with the above regulations, the Center for Veterinary Medicine (CVM) considers petfoods, not otherwise in violation of the statue or regulations, to be safe and suitable for consumption by pets regardless of the origin of the animal tissue used. CVM, which is a regulatory agency, has determined that the temperatures required for retort canning are sufficient to destroy pathogenic organisms. However, recent changes in CVM policy indicate that "the Center will consider regulatory action based on low-acid canned food violations alone where a report indicate a probable hazard to pets. CVM will also con-

sider regulatory action against canned petfood on the basis of use of decomposed animal tissue or use of tissue containing a violative drug residue" (FDA/ORA, 2002).

FDA does not approve, license, or issue permits for finished canned food products, including canned petfood, shipped in interstate commerce. However, all commercial processors of LACFRs are required to register their establishments and to file processing information for all canned products (21 CFR 110.3). This is done to ensure the safety of canned petfood for its intended purpose.

Homemade Diets

The vast majority of pet owners have chosen to feed their animals commercially prepared diets. However, for a variety of reasons, some owners prefer to prepare and feed homemade diets to their pets. This can be done successfully if the pet owner is willing to become fully knowledgeable concerning the pet's nutritional requirements; learn the critical aspects of diet formulation; identify and acquire the required ingredients needed for the diet; and develop effective processing technology to produce the diet safely on a routine basis. The decision to make homemade pet diets should not be made lightly because the owner is assuming full responsibility for the nutritional status of the pet. Consultation with a professional with sufficient advanced training to be able to formulate diets and/or assess the nutrient adequacy of a recipe is prudent.

DIET FORMULATION

The actual process of diet formulation involves the application of knowledge of energy, amino acid, mineral, and vitamin requirements for the target animal (Deyoe, 1976). From a conceptual standpoint, formulation is simply the process of selecting ingredients in specific amounts that contribute required and available nutrients to the diets so that the level of each required nutrient is met in the amount of diet consumed on a daily basis.

Two basic techniques are used in diet formulation: hand formulation and computer formulation. For the hand calculation technique, only a limited number of factors, both ingredients and nutrients, can be considered. In most instances the formulator will consider only major nutrients such as protein, calcium, phosphorus, and energy. Additionally, only a few ingredients are used (e.g., a grain, a vegetable protein meal, an animal protein meal, and a vitamin-mineral supplement). In most cases, precision is largely ignored.

All commercial companies and consulting nutritionists now use a computer-based process known as "linear programming." The value of linear programming is in the vast array of ingredients, nutrient requirements, and restrictions that it can deal with in just a few seconds.

Although dedicated least-cost (linear) programs are widely available, they are not inexpensive. Many of the more advanced programs have the National Research Council nutrient requirements for various species pre-loaded as well as numerous ingredient profiles. For computer-literate users, most spreadsheet programs of today have linear programming capabilities and can be set up to formulate diets using least cost as the default restriction.

Some proponents tout the nutritional superiority of "fixed" versus "variable" ingredient formulas. It is argued that the potential for batch-to-batch substitution of ingredients on the basis of cost may result in inconsistent nutrient content and product performance. While this position has merit, it must also be understood that any ingredient source is likely to change over time and that one shipment of ingredients, such as meat or bone meal and even soybean meal or grain, may differ distinctly in nutrient content from another. Adherence to a precisely fixed ingredient formula may not allow enough flexibility to ensure consistent nutrient content either. Thus, formulating on the basis of a fixed nutrient range rather than a fixed ingredient formula appears most prudent. Also, it must be noted that substitutions based on least cost are limited in the petfood industry because, unlike livestock feeds, ingredients must be declared by their specific names, not by "collective terms" (AAFCO, 2002). Thus, the costs of reprinting packaging to accommodate the change must be offset by the savings in production for it to have any value.

SUMMARY

The variety of petfood forms available today is mind-boggling, and new products are appearing almost daily. A summary of the major nutrient content of dry, semi-moist, and canned dog food is found in Table 12-1. The ranges are

TABLE 12-1 Nutrient Content of Dry, Semi-moist, and Canned Dog Foods

	As-Fed Basis	DM Basis
Dry		
Moisture (%)	6-10	0
Fat (%)	7-20	8-22
Protein (%)	16-30	18-32
Carbohydrate (%)	41-70	46-74
ME (kcal·kg^{-1})	2,800-4,050	3,000-4,500
Semi-moist		
Moisture (%)	15-30	0
Fat (%)	7-10	8-14
Protein (%)	17-20	20-28
Carbohydrate (%)	40-60	58-72
ME (kcal·kg^{-1})	2,550-2,880	3,000-4,000
Canned		
Moisture (%)	75	0
Fat (%)	5-8	20-32
Protein (%)	7-13	28-50
Carbohydrate (%)	4-13	18-57
ME (kcal·kg^{-1})	875-1,250	3,500-5,000

NOTE: ME = Metabolizable energy.
SOURCE: Case et al., 2000, Table 17-1.

similar for the various forms of cat food. However, given the variety of forms available and the innovative nature of the petfood industry, a true picture of all commercial petfoods in the market is simply not possible.

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13

Nutrient Composition of Ingredients Used in Dog and Cat Foods

Data in Tables 13-1 through 13-9 were compiled from commercial feed ingredient suppliers, published literature, and unpublished data provided by university researchers.[1] The tables include means and, when available, the standard deviation and number (*N*) of samples used to generate those statistics. Users should examine the standard deviation and *N* before using the mean value as an estimate of the nutritional content of a specific feed ingredient. Means derived from a large *N* will better reflect the total population. Means with a large standard deviation may represent the total population, but be a poor estimate for a specific sample. Common names are used to designate feed ingredients.

[1]An excellent source of information for feed ingredients not included here is contained in Chapter 11 of the report Nutrient Requirements of Swine, available online at http://www.nap.edu/catalog/6016.html (NRC, 1998).

TABLE 13-1 Proximate Analysis of Selected Feed Ingredients (as fed)[a]

Feed name/description		IFN[b]		DM[c] (%)	CP[d] (%)	Fat (%)	TDF[e] (%)	CF[f] (%)	Ash (%)	ME,[g] kcal/g (dog)	ME,[g] kcal/g (cat)
Ingredients of animal origin											
Bacon											
	Pork, cured			68.40	8.70	57.50	0.00		2.10		
			N	251	321	202	1		50		
Beef											
	Meat, mechanically separated			40.60	15.00	23.50	0.00		2.10	2.72	2.60
			N	56	56	64	1		56		
	Broth (or bouillon), dehydrated			96.70	16.00	8.90	0.00		48.20	2.38	2.34
			N	3	3	3	1		3		
	Heart, raw			24.40	17.10	3.80	0.00		1.00	1.13	1.11
			N	15	4	4	1		10		
	Kidney, raw			23.00	16.60	3.10	0.00		1.10	1.03	1.01
			N	28	5	9	1		11		
	Liver, raw			31.00	20.00	3.90	0.00		1.30	1.38	1.36
			N	50	6	15	1		11		
	Tripe, raw			18.60	14.60	4.00	0.00		0.40	0.94	0.92
			N	6	11	6	1		4		
Chicken											
	Meat and skin, raw			38.20	17.60	20.30	0.00		1.00	2.53	2.43
			N	1	1	1	1		1		
	Broth (or bouillon), dehydrated			97.70	16.70	13.90	0.00		49.20		
			N	4	4	4	1		4		
	Gizzard			23.80	18.20	4.20	0.00		0.90	1.13	1.11
			N	13	15	14	1		12		
	Liver			26.40	18.00	3.90	0.00		1.20	1.20	1.18
			N	18	13	54	1		12		
Egg											
	Dried, whole			96.60	47.20	41.10	0.00	0.00	3.60	5.91	5.70
			N	3	3	3	1	1	3		
Fish											
	Meal, menhaden	5-02-009		91.20	62.50	9.50		1.00	18.00	3.72	3.67
			N	136	148	144		1	114		
	Meal, tuna	5-02-023		93.00	53.00	11.00		5.00	25.00	3.35	3.30
			N	1	1	1		1	1		
	Meal, white	5-02-025		91.00	61.80	4.30		0.90	24.00	3.22	3.20
			N	2	2	2		2	1		
Lamb											
	Ground			40.50	16.60	23.40	0.00		0.90	2.77	2.65
			N	1	1	1	1		1		
	Liver			28.60	20.40	5.00	0.00		1.40	1.34	1.31
			N	17	1	1	1		1		
	Meat, mechanically separated			41.30	15.00	23.50	0.00		1.20	2.72	2.60
			N	5	1	6	1		1		
Meat											
	Meal, rendered	5-09-323		93.90	54.10	11.80		2.50	21.80	3.62	3.56
			N	79	67	33		1	13		
	Meal, with bone, rendered	5-00-388		94.00	50.90	9.80		2.80	19.20	3.61	3.56
			N	63	63	55		1	13		
Poultry											
	By-product meal	5-03-798		93.50	59.00	13.50		2.00	16.00	3.96	3.89
			N	2	2	2		2	1		
Shrimp											
	Meat, mixed species			24.10	20.30	1.70	0.00		1.20	1.00	1.00
			N	212	201	100	1		161		
Milk											
	Skimmed, dried	5-01-175		92.50	34.60	0.80		0.10	8.00	3.71	3.71
			N	2	2	2		2	1		

TABLE 13-1 (continued)

Feed name/description		IFN[b]		DM[c] (%)	CP[d] (%)	Fat (%)	TDF[e] (%)	CF[f] (%)	Ash (%)	ME,[g] kcal/g (dog)	ME,[g] kcal/g (cat)
Turkey											
	Mechanically deboned			30.90	13.30	16.00	0.00		1.10	1.97	1.89
			N	21	21	21	1		10		
Whey											
	Dried	4-01-182		93.50	12.50	0.80		0.10	9.70	3.65	3.64
			N	2	2	2		2	1		
Ingredients of plant origin											
Barley											
	Grain	4-00-549		90.20	12.30	2.20	17.30	5.30	2.30	3.81	3.80
			N	9	14	8	1	2	15		
Beet (sugar)											
	Pulp, dried	4-00-669		88.30	8.80	1.00		21.00	6.40	2.95	2.95
			N	200	183	124		1	55		
Carrots											
	Whole, raw			12.20	1.00	0.20	3.00	1.10	0.90	0.46	0.46
			N	238	183	29	1	1	47		
Cereal											
	Cereal by-product	4-00-466		88.50	8.10	3.30		1.50	2.90	3.99	3.97
			N	62	62	37		1	22		
Chicory											
	Root			20.00	1.40	0.20			0.90		
			N	1	1	1			1		
Corn, yellow											
	Bran, crude			95.30	8.40	0.90	85.50		0.40	3.84	3.84
			N	6	6	6	1		6		
	Distillers grain, dried	5-02-842		94.00	27.00	9.00		13.00	2.20	3.84	3.80
			N	1	1	1		1	1		
	Distillers grain w/ solubles, dried	5-02-843 and 5-28-236		90.20	26.80	9.00		8.50	4.70	3.92	3.88
			N	893	880	465		1	135		
	Gluten feed, dried	5-28-243 and 5-02-903		89.40	21.30	3.10		10.00	6.10	3.51	3.49
			N	132	187	69		1	26		
	Gluten meal	5-28-242		86.50	56.30	2.20		1.30	2.90	3.94	3.93
			N	67	58	43		1	20		
	Grits			90.00	8.80	1.20	1.60		0.40	3.64	3.64
			N	157	156	156	1		156		
	Grain	4-02-935		89.30	9.10	4.40		2.10	1.20	4.09	4.07
			N	12	9	6		2	5		
	Meal, degermed			88.40	8.50	1.70	7.40		0.60	3.59	3.59
			N	513	127	128	1		127		
	Meal, whole kernel			89.70	8.10	3.60	7.30		1.10	3.72	3.71
			N	10	7	7	1		7		
	Starch			91.70	0.30	0.10	0.90		0.10	3.67	3.67
			N	5	5	3	1		4		
	Syrup, dark			77.20	0.00	0.00	0.00		4.00	3.06	3.06
			N	5	1	5	1		4		
Flaxseed (linseed)											
	Whole			92.20	21.00	34.70	27.90	6.30	4.00	5.32	5.15
			N	3	3	3	2	1	3		
Molasses											
	Beet, sugar	4-00-668		78.00	6.70	0.10		0.00	9.00	3.64	3.64
			N	22	13	4		1	10		

TABLE 13-1 continued

Feed name/description		IFN[b]		DM[c] (%)	CP[d] (%)	Fat (%)	TDF[e] (%)	CF[f] (%)	Ash (%)	ME,[g] kcal/g (dog)	ME,[g] kcal/g (cat)
Oats											
	Grain	4-03-309		90.00	11.90	4.60		10.80	3.00	3.68	3.66
			N	177	309	146		1	104		
	Groats	4-03-331		92.00	16.00	6.00		2.60	2.20	4.11	4.08
			N	1	1	1		1	1		
Peas											
	Green, raw			21.10	5.40	0.40	5.10		0.90	0.83	0.83
			N	10	7	7	1		7		
Potato											
	Flesh and skin, raw			8.00	2.00	0.00	2.40		0.80	0.29	0.29
			N	9	9	9	9		9		
Rice											
	Bran	4-03-928		90.60	14.00	13.80		11.40	9.40	3.86	3.79
			N	73	87	78		1	69		
	Brewers (broken)	4-03-932		89.00	8.70	0.70		9.80			
			N	1	1	1		1			
	Brown, medium grain			87.60	7.50	2.70	3.40		1.30	3.59	3.57
			N	4	7	5	1		4		
	Flour, brown			88.00	7.20	2.80	4.60		1.50	3.60	3.58
			N	3	3	3	1		3		
	Flour, white			88.10	6.00	1.40	2.40		0.60	3.57	3.56
			N	2	2	2	1		2		
	Hulls	1-08-075		92.00	3.00	0.50		44.00	20.00	1.47	1.46
			N	1	1	1		1	1		
Sorghum											
	Grain	4-20-893		87.00	8.80	2.90		2.30			
			N	1	1	1		1			
Soybean											
	Flour, defatted			92.80	51.50	1.20	17.50		6.20	3.70	3.70
			N	6	6	6	1		2		
	Flour, full fat, roasted			96.20	38.10	21.90			5.90	4.84	4.73
			N	58	52	31			16		
	Hulls	1-04-560		90.90	12.60	2.40		36.50	4.40	2.49	2.48
			N	131	139	78		1	46		
	Meal, solvent, (44% CP)	5-20-637 and 5-04-604		89.10	44.50	1.40		7.00	5.90	3.56	3.55
			N	12	112	88		1	66		
	Meal, solvent, without hulls (48% CP)	5-20-638 and 5-04-612		89.50	48.20	1.00		3.90	5.70	3.66	3.66
			N	562	550	42		1	119		
Sugar											
	Granulated			100.00	0.00	0.00	0.00		0.00	4.00	4.00
			N	9	1	3	1		6		
	Brown			98.40	0.00	0.00	0.00		0.90	3.89	3.89
			N	5	1	1	1		5		
Wheat											
	Flour, whole grain			89.70	13.70	1.90	12.20		1.60	3.62	3.61
			N	15	16	10	1		14		
	Germ			88.90	23.20	9.70	13.20		4.20	3.87	3.82
			N	10	7	8	1		9		
	Germ meal	5-05-218		89.00	25.00	7.00		3.50	5.30	4.00	3.96
			N	1	1	1		1.00	1		
	Flour, white, unenriched			88.10	10.30	1.00	2.70		0.50	3.55	3.55
			N	72	61	29	1		61		
	Middlings	4-05-205		89.50	16.60	4.00		7.50	4.50	3.72	3.70
			N	294	246	212		1	87		
	Mill run			90.00	15.50	4.10		8.30	5.30	3.66	3.64
			N	1	1	1		1	1		

TABLE 13-1 continued

Feed name/description	IFN[b]		DM[c] (%)	CP[d] (%)	Fat (%)	TDF[e] (%)	CF[f] (%)	Ash (%)	ME,[g] kcal/g (dog)	ME,[g] kcal/g (cat)
Yeast										
Brewers, Torula, dried	7-05-534		93.00	47.90	2.30		2.60	8.00	3.69	3.68
		N	2	2	2		2	1		

[a]For each ingredient two numbers are given: the first is the % composition of each respective dietary component in the ingredient; the second, the number (N) of observations on which the data are based.
[b]International Feed Number.
[c]Dry Matter.
[d]Crude Protein.
[e]Total Dietary Fiber.
[f]Crude Fiber.
[g]Metabolizable Energy.

TABLE 13-2 Carbohydrate and Lignin Concentrations of Some Common Ingredients in Canine and Feline Foods (g/kg dry matter)[a]

			Low-Molecular-Weight Sugars								Soluble Noncellulosic Polysaccharides							
Common Name	No. of Samples	Genus/species	Monosaccharides	Sucrose	Raffinose	Stachyose	Total Sugars	Starch	Frutan	β-Glucan	Total S-NCP[b]	Rhamnose	Arabinose	Xylose	Mannose	Galactose	Glucose	Uronic Acids
Barley		*Hordeum vulgare*																
Hulled	10		4	12	5	1	21	587	4	42	56	0	6	6	2	1	39	2
Hulless	6		n.m.[e]	n.m.[e]	n.m.[e]	n.m.[e]	n.m.[e]	645	n.m.[e]	42	50	0	3	4	1	1	41	1
Dehulled	1		2	7	4	1	15	654	5	44	50	0	4	7	1	2	34	1
Hull meal	1		4	17	10	2	32	174	7	16	20	0	3	0	0	1	13	3
Maize	3	*Zea mays*	4	13	2	1	20	690	6	1	9	0	3	2	2	1	1	1
Feed meal	2		6	29	4	1	40	566	2	1	10	0	1	2	1	1	0	4
Gluten fraction	1		2	2	1	1	6	207	0	1	6	0	1	1	3	0	2	0
Gluten feed	2		6	25	5	2	41	282	2	2	34	0	7	7	0	3	2	15
Flour	2		4	6	1	0	10	902	2	1	8	0	3	3	1	1	0	1
Bran	2		5	21	4	1	32	376	4	2	32	0	6	5	1	2	6	12
Wheat	5	*Triticum aestivum*	3	11	4	2	19	651	15	8	25	0	7	9	2	2	4	1
Flour	2		1	8	3	3	17	820	16	4	16	0	3	7	0	2	2	2
Bran	3		7	30	12	4	53	222	20	24	29	0	7	10	1	2	8	2
Middlings	1		4	20	9	3	36	575	23	26	71	0	21	31	2	3	11	3
Oats		*Avena sativa*																
Hulled	3		2	11	3	2	17	468	3	28	40	0	3	2	2	2	28	3
Hulless	4		n.m.[e]	n.m.[e]	n.m.[e]	n.m.[e]	n.m.[e]	557	n.m.[e]	41	54	0	3	2	1	2	45	2
Feed meal	2		2	12	2	2	17	623	2	42	42	0	2	1	2	2	33	2
Rolled	1		2	12	3	2	19	646	1	42	48	0	4	2	0	2	38	2
Hull meal	1		4	7	2	1	14	213	2	14	13	0	2	0	1	0	8	1
Soybean		*Glycine max*																
Meal	6		7	70	10	47	137	27	—	—	63	1	9	2	5	16	6	25
Protein concentrate	1		4	0	2	14	21	69	—	—	81	1	13	5	2	30	2	27

TABLE 13-2 (continued)

Common Name	No. of Samples	Genus/species	Insoluble Noncellulosic Polysaccharides										Carbohydrates and Lignin			
			Total I-NCP[c]	Rhamnose	Arabinose	Xylose	Mannose	Galactose	Glucose	Uronic Acids	Cellulose	Total NSP[d]	Klason Lignin	Dietary Fiber	Analyzed	Calculated
Barley		*Hordeum vulgare*														
Hulled	10		88	0	22	50	2	2	8	4	43	186	35	221	834	823
Hulless	6		64	0	17	24	3	2	17	1	10	124	9	133	n.m.[e]	n.m.[e]
Dehulled	1		58	0	17	29	2	0	8	2	19	127	19	146	819	834
Hull meal	1		267	0	48	184	3	5	12	15	192	478	115	594	806	786
Maize	3	*Zea mays*	66	0	19	28	1	4	9	6	22	97	11	108	823	830
Feed meal	2		114	0	32	46	1	8	10	16	33	156	18	174	783	774
Gluten fraction	1		14	0	3	3	0	0	6	2	5	25	0	25	238	252
Gluten feed	2		242	0	61	97	4	15	14	51	75	351	32	383	708	710
Flour	2		13	0	3	3	0	0	5	2	0	21	4	25	940	904
Bran	2		240	0	66	111	3	18	10	32	83	354	25	379	791	775
Wheat	5	*Triticum aestivum*	74	0	22	38	1	2	7	4	20	119	19	138	823	814
Flour	2		17	0	6	8	1	0	4	0	3	35	0	35	887	864
Bran	3		273	0	83	138	4	7	27	13	72	374	75	449	704	707
Middlings	1		101	0	27	36	6	4	21	7	19	190	11	201	836	809
Oats																
Hulled	3		110	0	15	78	1	5	5	7	82	232	66	298	787	770
Hulless	4		49	0	10	21	2	2	11	3	14	116	32	148	n.m.[e]	n.m.[e]
Feed meal	2		39	0	8	15	1	1	10	3	8	89	19	108	749	748
rolled	1		37	0	6	11	2	1	13	3	6	91	15	106	772	766
Hull meal	1		295	0	26	212	1	9	12	35	196	505	148	653	882	855
Soybean		*Glycine max*														
Meal	6		92	2	17	17	8	25	1	23	62	217	16	233	400	416
Protein concentrate	1		67	1	12	7	7	24	2	14	30	177	8	185	275	277

[a]Adapted from Bach-Knudsen, 1997.
[b]Soluble noncellulosic polysaccharides.
[c]Insoluble noncellulosic polysaccharides.
[d]Nonstarch polysaccharides.
[e]Not measured.

TABLE 13-3 Total Fat Concentration and Fatty Acid Composition of Selected Feed Ingredients

Ingredient		Total Fat (% as is)	Percent of total fatty acids																
			10:0	12:0	13:0	13:1	14:0	14:1	15:0	16:0	16:1n-7	17:0	17:1	18:0	18:1n-9	18:1n-7	18:2n-6	18:3n-6	18:3n-3	20:0
Chicken Meal		12.90	0.00	0.04	0.00	0.00	0.60	0.21	0.08	23.88	6.50	0.16	0.12	7.58	36.41	3.07	14.70	0.64	0.60	0.18
$N = 64$	SD	1.67	0.01	0.03	0.00	0.00	0.10	0.08	0.03	1.01	0.66	0.06	0.11	0.77	1.43	0.43	3.11	2.69	0.19	0.10
Lamb Meal		13.80	0.07	0.17	0.01	0.01	2.71	0.17	0.63	21.05	1.72	1.56	0.54	22.00	30.49	5.90	2.01	0.29	1.05	0.36
$N = 42$	SD	1.63	0.05	0.10	0.04	0.03	0.69	0.10	0.15	1.02	0.41	0.22	0.33	3.22	1.35	1.04	0.53	0.29	0.31	0.22
Beef Meal		13.16	0.05	0.09	0.00	0.00	2.39	0.41	0.42	22.79	2.68	1.17	0.47	17.28	32.10	5.74	5.51	0.09	0.53	0.34
$N = 8$	SD	0.88	0.02	0.02	0.00	0.00	0.49	0.14	0.29	1.82	0.20	0.39	0.30	1.96	4.26	1.83	2.17	0.18	0.21	0.21
Wheat Bran		4.93	0.00	0.00	0.00	0.00	0.12	0.00	0.13	16.63	0.15	0.12	0.00	1.11	17.30	1.04	56.11	0.00	4.40	0.23
$N = 4$	SD	0.38	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.79	0.02	0.01	0.00	0.05	0.18	0.10	0.84	0.00	0.11	0.02
Wheat Flour		3.41	0.00	0.00	0.00	0.00	0.16	0.00	0.14	17.26	0.09	0.12	0.00	1.73	14.10	1.25	58.34	0.00	3.41	0.31
$N = 6$	SD	0.58	0.00	0.00	0.00	0.00	0.12	0.00	0.07	1.14	0.07	0.04	0.00	0.88	1.92	0.36	0.87	0.00	0.60	0.17
Whole Wheat		2.98	0.00	0.00	0.00	0.00	0.08	0.00	0.10	17.39	0.16	0.10	0.04	1.13	13.79	1.29	58.97	0.00	3.98	0.18
$N = 4$	SD	0.17	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.28	0.01	0.03	0.05	0.09	0.29	0.12	0.96	0.00	0.11	0.03
Rice Bran		4.15	0.00	0.02	0.00	0.00	0.45	0.01	0.04	16.70	0.22	0.03	0.00	2.00	40.26	2.34	31.93	0.00	1.25	0.73
$N = 8$	SD	0.50	0.00	0.01	0.00	0.00	0.34	0.15	0.23	0.42	0.37	0.43	0.07	2.53	2.75	0.79	4.66	0.15	0.04	0.13
Rice Protein		6.73	0.00	0.00	0.00	0.00	0.70	0.01	0.03	23.79	0.15	0.06	0.02	2.23	29.31	1.09	38.89	0.00	1.39	0.51
$N = 4$	SD	0.15	0.00	0.00	0.00	0.00	0.23	0.02	0.00	3.00	0.02	0.00	0.02	0.05	2.51	0.11	0.58	0.00	0.07	0.04
Rice Gluten		5.15	0.00	0.00	0.00	0.00	0.84	0.00	0.05	29.84	0.11	0.00	0.00	2.83	26.01	1.23	33.30	0.00	0.91	0.61
$N = 2$	SD	0.05	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.62	0.03	0.00	0.00	0.06	0.16	0.22	0.19	0.00	0.04	0.01
Rice (Whole)		1.90	0.00	0.00	0.00	0.00	0.79	0.00	0.02	19.14	0.15	0.00	0.00	4.11	34.67	1.26	34.61	0.00	1.30	0.65
$N = 8$	SD	0.70	0.00	0.00	0.00	0.00	0.16	0.00	0.02	1.46	0.06	0.03	0.00	1.74	2.10	0.44	2.49	0.00	0.25	0.07
Corn Gluten		5.97	0.00	0.00	0.00	0.00	0.05	0.02	0.03	11.48	0.16	0.08	0.02	2.24	25.09	0.96	55.46	0.00	2.12	0.50
$N = 6$	SD	1.31	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.28	0.02	0.00	0.02	0.03	0.30	0.05	0.14	0.00	0.03	0.03
Beet Pulp		1.70	0.00	0.00	0.00	0.00	0.35	0.00	0.40	20.16	0.45	0.07	0.06	1.46	14.66	1.14	47.34	0.11	3.78	0.09
$N = 2$	SD	0.10	0.00	0.00	0.00	0.00	0.05	0.00	0.06	0.03	0.07	0.07	0.06	0.48	0.57	0.02	0.25	0.00	0.20	0.00
Herring Meal		12.40	0.06	0.05	0.00	0.00	4.46	0.08	0.41	16.24	3.89	0.08	0.00	3.37	16.65	2.50	4.48	0.09	0.94	0.18
$N = 2$	SD	0.00	0.00	0.01	0.00	0.00	0.39	0.00	0.03	0.39	0.06	0.00	0.00	0.31	0.19	0.09	0.37	0.01	0.02	0.00

TABLE 13-3 (continued)

Ingredient		20:1n-9	20:2n-6	20:3n-9	20:3n-6 (5,11,14)	20:3n-6 (8,11,14)	20:3n-3	20:4n-6	20:5n-3	22:0	22:1n-9	22:2n-6	23:0	22:4n-6	22:5n-6	22:5n-3	24:0	22:6n-3	24:1
Chicken Meal		0.32	0.25	0.01	0.01	0.28	0.01	1.37	0.02	0.15	0.01	0.03	0.00	0.36	0.05	0.09	0.16	0.11	0.23
$N = 64$	SD	0.11	0.08	0.04	0.06	0.14	0.05	0.37	0.08	0.06	0.03	0.05	0.00	0.10	0.06	0.06	0.06	0.04	0.08
Lamb Meal		0.30	0.10	0.00	0.00	0.07	0.00	0.62	0.21	0.23	0.06	0.04	0.02	0.11	0.10	0.31	0.29	0.23	0.27
$N = 42$	SD	0.23	0.20	0.00	0.00	0.14	0.00	0.25	0.13	0.12	0.14	0.09	0.07	0.09	0.29	0.15	0.16	0.11	0.17
Beef Meal		0.50	0.26	0.00	0.00	0.28	0.16	0.62	0.02	0.12	0.20	0.08	0.00	0.17	0.00	0.10	0.13	0.11	0.13
$N = 8$	SD	0.21	0.26	0.00	0.00	0.24	0.30	0.23	0.05	0.03	0.23	0.14	0.00	0.07	0.00	0.05	0.03	0.07	0.04
Wheat Bran		0.91	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.12	0.01	0.00	0.04	0.00	0.00	0.28	0.00	0.13
$N = 4$	SD	0.09	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.03	0.00	0.05	0.00	0.00	0.02	0.00	0.02
Wheat Flour		0.82	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.18	0.00	0.00	0.02	0.00	0.00	0.42	0.00	0.15
$N = 6$	SD	0.19	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.00	0.00	0.03	0.00	0.00	0.08	0.00	0.07
Whole Wheat		0.95	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.16	0.00	0.00	0.04	0.00	0.00	0.37	0.00	0.13
$N = 4$	SD	0.07	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.05	0.00	0.00	0.08	0.00	0.00	0.03	0.00	0.03
Rice Bran		0.44	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.82	0.00	0.17	0.00	0.14	0.00	0.00	2.08	0.00	0.00
$N = 8$	SD	0.11	0.21	0.00	0.00	0.23	0.21	0.00	0.05	0.11	0.17	0.10	0.00	0.07	0.00	0.00	0.37	0.33	0.23
Rice Protein		0.36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.00	0.02	0.00	0.03	0.00	0.00	0.52	0.00	0.00
$N = 4$	SD	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.00	0.03	0.00	0.00	0.03	0.00	0.00
Rice Gluten		0.17	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.35	0.00	0.00	0.00	0.00	0.00	0.00	1.01	0.00	0.00
$N = 2$	SD	0.04	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00
Rice (Whole)		0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.00	0.11	0.00	0.04	0.00	0.00	0.75	0.00	0.00
$N = 8$	SD	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.07	0.00	0.03	0.00	0.00	0.04	0.00	0.00
Corn Gluten		0.27	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.00	0.00	0.00	0.09	0.00	0.52	0.52	0.00	0.00
$N = 6$	SD	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.01	0.00	0.08	0.08	0.00	0.00
Beet Pulp		0.48	1.19	0.37	0.00	0.00	0.00	0.10	0.00	0.77	0.20	0.08	0.00	1.65	0.43	0.06	0.06	0.00	0.18
$N = 2$	SD	0.00	0.06	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.05	0.01	0.01	0.01	0.00	0.01
Herring Meal		6.50	0.22	0.00	0.00	0.04	0.00	0.67	5.49	0.14	10.36	0.18	0.00	0.19	0.00	0.63	0.63	11.28	1.62
$N = 2$	SD	0.08	0.01	0.00	0.00	0.00	0.00	0.02	0.30	0.01	0.04	0.01	0.00	0.02	0.00	0.03	0.03	0.08	0.09

TABLE 13-4 Fatty Acid Composition of Selected Fats and Oils[a]

		Selected Fatty Acids, % of Total Fatty Acids								
Lipid	IFN[b]	<C10	C12:0	C14:0	C16:0	C1:1	C18:0	C18:1	C18:2n-6	C18:3n-3
Animal fats										
Beef tallow	4-08-127	0	0.9	2.7	24.9	4.2	18.9	36.0	3.1	0.6
Choice white grease		0.2	0.2	1.9	21.5	5.7	14.9	41.1	11.6	0.4
Lard	4-04-790	0.1	0.2	1.3	23.8	2.7	13.5	41.2	10.2	1.0
Poultry fat	4-09-319	0.0	0.1	0.9	21.6	5.7	6.0	37.3	19.5	1.0
Restaurant grease				1.9	16.2	2.5	10.5	47.5	17.5	1.9
Fish oils										
Anchovy				7.4	17.4	10.5	4.0	11.6	1.2	0.8
Herring	7-08-048		0.2	6.4	12.7	8.8	0.9	12.7	1.1	0.6
Menhaden	7-08-049			7.3	19.0	9	4.2	13.2	1.3	0.3
Capelin	7-16-709			7.9	11.1	11.1	1.0	17.0	1.7	0.4
Cod liver	7-01-994			3.2	13.5	9.8	2.7	23.7	1.4	0.6
Redfish				4.9	13.2	13.2	2.2	13.3	0.9	0.5
Salmon (sea caught)				3.7	10.2	8.7	4.7	18.6	1.2	0.6
Vegetable oils										
Babassu		11.1	42.4	16.8	9.3		3.5	14.2	2.4	
Borage		0.0	0.0	0.0	11.5		4.9	19.5	40.3	
Canola (rapeseed)	4-06-144	0.0	0.0	0.0	4.0	0.2	1.8	56.1	20.3	9.3
Coconut	4-09-320	14.1	44.6	16.8	8.2	0.0	2.8	5.8	1.8	0.0
Corn	4-07-882	0.0	0.0	0.0	10.9	0.0	1.8	24.2	59.0	0.7
Linseed	4-14-502	0.0	0.0	0.0	5.3	0.0	4.1	20.2	12.7	53.3
Cottonseed	4-20-836	0.0	0.0	0.8	22.7	0.8	2.3	17	51.5	0.2
Olive		0.0	0.0	0.0	11.0	0.8	2.2	72.5	7.9	0.6
Palm		0.0	0.1	1.0	43.5	0.3	4.3	36.6	9.1	0.2
Palm kernel		6.7	48.2	16.2	8.4		2.5	15.3	2.3	
Peanut	4-03-658	0.0	0.0	0.1	9.5	0.1	2.2	44.8	32.0	
Safflower	4-20-526	0.0	0.0	0.1	6.2	0.4	2.3	11.7	74.1	0.4
Safflower (high oleic)				0.1	6.8	0.1	2.3	12.0	77.7	0.4
Sesame		0.0	0.0	0.0	8.9	0.2	4.8	39.3	41.3	0.3
Soybean	4-07-983	0.0	0.0	0.1	10.3	0.2	3.8	22.8	51.0	6.8
Sunflower (high oleic)					3.7	0.1	5.4	81.3	9.0	
Sunflower	4-20-833	0.0	0.0	0.0	5.4	0.2	3.5	45.3	39.8	0.2

[a]Certain fats and oils have significant amounts of fatty acids other than those listed above. Examples include:
Butter oil: C4:0, 3.65%; C6:0, 2.2%; C15:0, 2.1%; C14:1, 0.8%
Peanut oil: C24:0, 1.5%
Rapeseed (high erucic acid rape oil): C24:0, 1.0%; C22:1, 41.1%; C20:2, 0.7%
Canola (low erucic acid rape) oil: C24:0 0.2%; C22:1, 0.7%; C20:2, 0.0%
Borage seed oil: C16:0, 11.5%; C18:0, 4.9%; C18:1n-9, 19.5%; C18:2n-6, 40.3%;C18:3n-6, 22.1%
Evening primrose oil: C16:0, 6.5%; C18:0, 1.8%; C18:1n-9, 8.6%; C18:2n-6, 73.5%; C18:3n-6, 8.7%
Black currant seed oil: C16:0, 6.7%; C18:0, 1.6%; C18:1n-9, 11.3%; C18:2n-6, 47.1%, C18:3n-6, 15.3%; C18:3n-3, 13.1%
[b]International Feed Number.
[c]Saturated fatty acids.
[d]Polyunsaturated fatty acids.
[e]Monosaturates are not included in this calculation.
SOURCE: Belch and Hill, 2000; Khan and Shahidi, 2000; Senanayake and Shahidi, 1999; Spurvey and Shahidi, 2000.

C18:4n-3	C20:1	C20:4n-6	C20:5n-3	C22:1	C22:5n-3	C22:6n-3	>C20	Total S[c] (%)	Total PUFA[d] (%)	PUFA:S[e] Ratio	Iodine Value	Total n-6	Total n-3
							0.3	47.4	3.7	0.08	44.0	3.1	0.6
							1.8	38.7	12.0	0.31	60.0	11.6	0.4
							1.0	38.9	11.2	0.29	64.0	10.2	1.0
							1.2	28.6	20.5	0.71	78.0	19.5	1.0
							1.0	28.6	19.4	0.68	75.0	17.5	1.9
3.0	1.6	0.1	17.0	1.2	1.6	8.8		28.8	35.3	1.23		1.3	31.2
1.7	14.1	0.3	8.4	20.8	0.8	4.9		20.2	52.7	2.61		1.4	17.8
2.8	2.0	0.2	11	0.6	1.9	9.1		30.5	29.2	0.95		1.5	25.1
2.1	18.9	0.1	4.6	14.7	0.3	3.0		20.0	45.8	2.29		1.8	10.4
0.9	7.4	1.6	11.2	5.1	1.7	12.6		19.4	42.5	2.19		3.0	27.0
1.1	17.2	0.3	8.0	18.9	0.6	8.9		20.3	56.4	2.78		1.2	19.1
2.1	8.4	0.9	12.0	5.5	2.9	13.8		18.6	47.4	2.55		2.1	31.4
							0.1	83.1	2.4	0.03	15.0	2.4	
							3.6	5.8	29.6	5.10	118.0	20.3	9.3
								86.5	1.8	0.02	10.0	1.8	0.0
								12.7	59.7	4.7	125.0	59.0	0.7
								9.4	66.0	7.02		12.7	53.3
							0.1	25.8	51.7	2.0	105.0	51.5	0.2
							0.3	13.2	8.5	0.64	86.0	7.9	0.6
							0.1	48.9	9.3	0.19	15.0	9.1	0.2
							0.2	82.0	2.3	0.03	50.0	2.3	
							6.4	11.8	32	2.71	92.0	32.0	
								8.6	74.5	8.66	140.0	74.1	0.4
	0.1						0.5	9.2	78.2	8.5	140.0	77.7	0.4
							0.2	13.7	41.6	3.04	110.0	41.3	0.3
							0.2	14.2	57.8	4.07	130.0	51.0	6.8
							0.4	9.1	9.0	0.99	85.0	9.0	
								8.9	40.0	4.49	133.0	39.8	0.2

TABLE 13-5 Amino Acid Composition of Selected Feed Ingredients (% as fed)[a]

Feed Name Description	IFN[b]		DM[c] (%)	CP[d] (%)	Arg (%)	His (%)	Ile (%)	Leu (%)	Lys (%)	Met (%)	Cys (%)	Phe (%)	Tyr (%)	Thr (%)	Trp (%)	Tau (%)	Val (%)
Ingredients of animal origin																	
Bacon																	
Pork, cured			68.40	8.70	0.53	0.25	0.35	0.60	0.64	0.19	0.09	0.33	0.25	0.33	0.08		0.42
		N	251	321	9	10	10	10	10	10	4	10	10	10	4		10
Beef																	
Meat, mechanically separated			40.60	15.00	1.15	0.44	0.58	1.20	1.16	0.43	0.23	0.64	0.38	0.47	0.17	0.008	0.92
		N	56	56	30	30	30	30	30	30	30	30	30	30	1	1	30
Broth (or bouillon), dehydrated			96.70	16.00													
		N	3	3													
Heart, raw			24.40	17.10	1.14	0.47	0.75	1.51	1.41	0.44	0.22	0.77	0.62	0.80	0.19	0.065	0.89
		N	15	4	1	1	1	1	1	1	1	1	1	1	1	3	1
Kidney, raw			23.00	16.60	0.97	0.43	0.68	1.33	1.10	0.35	0.05	0.50	0.62	0.80	0.23	0.023	1.04
		N	28	5	4	4	4	4	4	4	4	4	4	4	3	9	4
Liver, raw			31.00	20.00	1.26	0.55	0.92	1.88	1.39	0.51	0.31	1.07	0.79	0.92	0.29	0.069	1.24
		N	50	6	1	1	1	1	1	1	1	1	1	1	1	8	1
Tripe, raw			18.60	14.60	1.00	0.36	0.59	0.95	1.04	0.32	0.17	0.47	0.40	0.50	0.11		0.61
		N	6	11	6	5	6	6	7	9	4	8	7	7	5		6
Chicken																	
Meat and skin, raw			38.20	17.60	1.10	0.52	0.88	1.28	1.43	0.47	0.23	0.68	0.57	0.73	0.20		0.85
		N	1	1	1	1	1	1	1	1	1	1	1	1	1		1
Broth (or bouillon), dehydrated			97.70	16.70													
		N	4	4													
Gizzard			23.80	18.20	1.31	0.37	0.86	1.28	1.26	0.48	0.24	0.76	0.55	0.84	0.16		0.82
		N	13	15	1	1	1	1	1	1	1	1	1	1	1		1
Liver			26.40	18.00	1.10	0.48	0.95	1.62	1.36	0.43	0.24	0.89	0.63	0.80	0.25	0.110	1.13
		N	18	13	1	1	1	1	1	1	1	1	1	1	1	1	1
Egg																	
Dried, whole			96.60	47.20	2.84	1.12	2.58	4.05	3.40	1.48	1.10	2.52	1.93	2.27	0.58		2.89
		N	3	3	1	1	1	1	1	1	1	1	1	1	1		1
Fish																	
Meal, menhaden	5-02-009		91.20	62.50	3.64	1.64	2.48	4.46	4.74	1.73	0.53	2		2.69	0.58	0.320	2.91
		N	136	148	2	2	2	2	2	2	2	2		2	2	2	2
Meal, tuna	5-02-023		93.00	53.00	3.20	1.80	2.40	3.80	3.90	1.50	0.40	2.50		2.50	0.71	0.106	2.80
		N	1	1	1	1	1	1	1	1	1	1		1	1	6	1
Meal, white	5-02-025		91.00	61.08	4.11	1.64	2.91	4.43	4.42	1.67	0.75	2.54	1.83	2.59	0.69		2.48
		N	2	2	2	2	2	2	2	2	2	2	1	2	2		2
Lamb																	
Ground			40.50	16.60	0.98	0.52	0.80	1.29	1.46	0.43	0.20	0.67	0.56	0.71	0.19		0.89
		N	1	1	1	1	1	1	1	1	1	1	1	1	1		1
Liver			28.60	20.40	1.14	0.48	0.88	1.67	1.10	0.44	0.21	0.91	0.73	0.88	0.24		1.12
		N	17	1	6	6	6	6	6	6	6	6	6	6	6		6
Meat, mechanically separated			41.30	15.00	1.06	0.53	0.84	1.14	1.14	0.42		0.58		0.53			0.72
		N	5	1	1	1	1	1	1	1		1		1			1
Meat																	
Meal, rendered	5-09-323		93.90	54.10	3.82	1.11	1.60	3.41	2.91	0.77	0.61	1.93		1.83	0.36		2.40
		N	79	67	436	436	436	436	436	436	436	436		436	436		436
Meal, with bone, rendered	5-00-388		94.00	50.90	3.55	0.96	1.41	3.12	2.64	0.71	0.52	1.71	1.20	1.67	0.30		2.14
		N	63	63	228	228	228	228	228	228	228	228	1	228	228		228

Poultry																	
	By-product meal	5-03-798		93.50	59.00	3.89	1.34	2.25	4.20	2.84	1.02	0.99	2.04	1.68	2.10	0.46	0.305	2.76
			N	2	2	2	2	2	2	2	2	2	2	1	2	2	12	2
Shrimp																		
	Meat, mixed species			24.10	20.30	1.78	0.41	0.99	1.61	1.77	0.57	0.23	0.86	0.68	0.82	0.28	0.039	0.96
			N	212	201	1	1	1	1	1	1	1	1	1	1	1	1	1
Milk																		
	Skimmed, dried	5-01-175		92.50	34.60	1.16	0.94	1.97	3.45	2.70	0.94	0.36	1.67	1.83	1.67	0.48	0.007	2.33
			N	2	2	2	2	2	2	2	2	2	2	1	2	2	1	2
Turkey																		
	Mechanically deboned			30.90	13.30	0.87	0.50	0.50	1.08	1.15	0.37	0.10	0.55	0.47	0.64	0.11	0.093	0.54
			N	21	21	1	1	1	1	1	1	1	1	1	1	1	3	1
Whey																		
	Dried	4-01-182		93.50	12.50	0.37	0.19	0.86	1.20	1.04	0.20	0.30	0.37	0.25	0.85	0.20	0.066	0.69
			N	2	2	2	2	2	2	2	2	2	2	1	2	2	1	2
Ingredients of plant origin																		
Barley																		
	Grain	4-00-549		90.20	12.30	0.62	0.28	0.45	0.85	0.47	0.24	0.27	0.70	0.36	0.42	0.20		0.61
			N	9	14	62	62	62	62	67	63	40	62	59	62	30		62
Beet (sugar)																		
	Pulp, dried	4-00-669		88.30	8.80	0.29	0.22	0.28	0.47	0.41	0.10	0.09	0.27	0.40	0.31	0.08		0.42
				200	183	13	13	13	13	13	13	13	13	1	13	13		13
Carrots																		
	Whole, raw			12.20	1.00	0.04	0.02	0.04	0.04	0.04	0.01	0.01	0.03	0.02	0.04	0.01		0.04
			N	238	183	59	59	60	60	64	64	12	60	13	60	57		60
Cereal																		
	Cereal by-product	4-00-466		88.50	8.10	0.40	0.20	0.36	0.80	0.30	0.16	0.16	0.40		0.28	0.09		0.40
			N	62	62	1	1	1	1	1	1	1	1		1	1		1
Chicory																		
	Root			20.00	1.40													
			N	1	1													
Corn, yellow																		
	Bran, crude			95.30	8.40													
			N	6	6													
	Distillers grain, dried	5-02-842		94.00	27.00	1.00	0.60	0.93	2.60	0.90	0.45	0.32	0.60		0.30	0.21		1.20
			N	1	1	1	1	1	1	1	1	1	1		1	1		1
	Distillers grain with solubles, dried	5-02-843 and 5-28-236		90.20	26.80	1.08	0.55	0.99	2.58	0.60	0.50	0.49	1.30		0.92	0.23		1.26
			N	893	880	13	13	13	13	13	13	13	13		13	13		13
	Gluten feed, dried	5-28-243 and 5-02-903		89.40	21.30	0.83	0.63	0.65	1.91	0.58	0.36	0.46	0.78		0.75	0.12		0.96
			N	132	187	12	12	12	12	12	12	12	12		12	12		12
	Gluten meal	5-28-242		86.50	56.30	1.80	1.20	2.31	9.43	0.95	1.33	1.01	3.57	3.07	1.90	0.30		2.61
			N	67	58	119	119	119	119	119	119	119	119	1	119	119		119
	Grits			90.00	8.80	0.44	0.27	0.31	1.08	0.25	0.18	0.16	0.43	0.36	0.33	0.06		0.44
			N	157	156	1	1	1	1	1	1	1	1	1	1	1		1
	Grain	4-02-935		89.30	9.10	0.47	0.28	0.33	1.15	0.26	0.20	0.17	0.46	0.37	0.35	0.07		0.47
			N	12.00	9	33	21	37	37	103	36	32	37	36	37	18		36

TABLE 13-5 (continued)

Feed Name	Description	IFN		DM (%)	CP (%)	Arg (%)	His (%)	Ile (%)	Leu (%)	Lys (%)	Met (%)	Cys (%)	Phe (%)	Tyr (%)	Thr (%)	Trp (%)	Tau (%)	Val (%)
	Meal, degermed			88.40	8.50													
			N	513	127													
	Meal, whole kernel			89.70	8.10	0.41	0.25	0.29	1.00	0.23	0.17	0.15	0.40	0.33	0.31	0.06		0.41
			N	10	7	1	1	1	1	1	1	1	1	1	1	1		1
	Starch			91.70	0.30	0.01	0.01	0.01	0.04	0.01	0.01	0.01	0.01	0.01	0.01	0.00		0.01
			N	5	5	11	11	11	11	68	10	10	11	11	11	76		10
	Syrup, dark			77.20	0.00													
			N	5	1													
Flaxseed (linseed)																		
	Whole			92.20	21.00													
			N	3.00	3.00													
Molasses																		
	Beet, sugar	4-00-668		78.00	6.70	3.25	1.05	2.94	2.38		0.15	0.55	1.79		1.04	0.30		2.22
			N	22	13	1	1	1	1		1	1	1		1	1		1
Oats																		
	Grain	4-03-309		90.00	11.90	0.81	0.29	0.45	0.87	0.50	0.20	0.33	0.61	0.53	0.41	0.14		0.62
			N	177	309	19	19	19	19	19	19	19	19	1	19	19		19
	Groats	4-03-331		92.00	16.00	0.90	0.25	0.50	1.00	0.45	0.20	0.26	0.65		0.50	0.18		0.65
			N	1	1	1	1	1	1	1	1	1	1		1	1		1
Peas																		
	Green, raw			21.10	5.40	0.43	0.11	0.20	0.32	0.32	0.08	0.03	0.20	0.11	0.20	0.04		0.24
			N	10	7	1	1	1	1	1	1	1	1	1	1	1		1
Potato																		
	Flesh and skin, raw			8.00	2.00	0.10	0.05	0.08	0.12	0.13	0.03	0.03	0.09	0.08	0.08	0.03		0.12
			N	9	9	9	9	7	7	7	7	6	7	6	7	6		7
Rice																		
	Bran	4-03-928		90.60	14.00	1.09	0.39	0.48	0.99	0.65	0.29	0.31	0.66	0.42	0.54	0.16		0.73
			N	73	87	15	15	15	15	15	15	15	15	1	15	15		15
	Brewers (broken)	4-03-932		89.00	8.70	0.74	0.26	0.37	0.74	0.43	0.22	0.21	0.48	0.33	0.36	0.10		0.54
			N	1	1	1	1	1	1	1	1	1	1	1	1	1		1
	Brown, medium grain			87.60	7.50	0.57	0.19	0.32	0.62	0.29	0.17	0.09	0.39	0.28	0.28	0.10		0.44
			N	4	7	1	1	1	1	1	1	1	1	1	1	1		1
	Flour, brown			88.00	7.20													
			N	3	3													
	Flour, white			88.10	6.00	0.52	0.15	0.24	0.49	0.21	0.14	0.11	0.32	0.31	0.21	0.07		0.35
			N	2	2	30	30	30	30	31	19	27	29	29	30	20		30
	Hulls	1-08-075		92.00	3.00													
			N	1	1													
Sorghum																		
	Grain	4-20-893		87.00	8.80	0.35	0.22	0.35	1.14	0.21	0.16	0.17	0.47	0.34	0.29	0.08		0.44
			N	1	1	1	1	1	1	1	1	1	1	1	1	1		1

Soybean																	
	Flour, defatted			92.80	51.50	3.65	1.27	2.28	3.93	3.13	0.63	0.76	2.45	1.78	2.04	0.68	2.35
			N	6	6	1	1	1	1	1	1	1	1	1	1	1	1
	Flour, full fat, roasted			96.20	38.10	2.70	0.94	1.69	2.83	2.32	0.47	0.56	1.82	1.32	1.51	0.51	1.74
			N	58	52	1	1	1	1	1	1	1	1	1	1	1	1
	Hulls	1-04-560		90.90	12.60	0.65	0.36	0.49	0.82	0.79	0.15	0.22	0.55		0.45	0.14	0.58
			N	131	139	8	8	8	8	8	8	8	8		8	8	8
	Meal, solvent, (44% CP)	5-20-637 and 5-04-604		89.10	44.50	3.28	1.23	2.03	3.47	2.79	0.64	0.68	2.34	1.91	1.77	0.57	2.09
			N	12	112	346	346	346	346	346	346	346	346	1	346	346	346
	Meal, solvent, without hulls (48% CP)	5-20-638 and 5-04-612		89.50	48.20	3.52	1.33	2.20	3.76	3.03	0.69	0.72	2.53	1.95	1.91	0.61	2.23
			N	562	550	296	296	296	296	296	296	296	296	1	296	296	296
Sugar																	
	Granulated			100.00	0.00												
			N	9	1												
	Brown			98.40	0.00												
			N	5	1												
Wheat																	
	Flour, whole grain			89.70	13.70	0.64	0.32	0.51	0.93	0.38	0.21	0.32	0.65	0.40	0.40	0.21	0.62
			N	15	16	26	26	25	25	26	26	20	25	24	25	12	25
	Germ			88.90	23.20	1.87	0.64	0.85	1.57	1.47	0.46	0.46	0.93	0.70	0.97	0.32	1.20
			N	10	7	13	13	13	13	13	13	13	13	12	13	3	13
	Germ meal	5-05-218		89.00	25.00	1.83	0.62	0.79	1.10	1.37	0.42	0.46	0.93		0.94	0.30	1.12
			N	1	1	1	1	1	1	1	1	1	1		1	1	1
	Flour, white, unenriched			88.10	10.30	0.42	0.23	0.36	0.71	0.23	0.18	0.22	0.52	0.31	0.28	0.13	0.42
			N	72	61	51	51	68	68	69	67	63	58	56	67	39	58
	Middlings	4-05-205		89.50	16.60	0.97	0.45	0.57	1.10	0.60	0.26	0.34	0.73	0.45	0.51	0.21	0.77
			N	294	246	121	121	121	121	121	121	121	121	1	121	121	121
	Mill run			90.00	15.50												
			N	1	1												
Yeast																	
	Brewers, Torula, dried	7-05-534		93.00	47.90	2.60	1.40	2.90	3.50	3.80	0.80	0.60	3.00		2.60	0.50	0.011	2.90
			N	2	2	1	1	1	1	1	1	1	1		1	1	3	1

[a]For each ingredient two numbers are given: the first is the % composition of each respective amino acid in the ingredient; the second, the number (N) of observations on which the data are based.
[b]International Feed Number.
[c]Dry matter.
[d]Crude protein.

TABLE 13-6 Mineral Content of Selected Ingredients (% or mg/kg, as fed)[a]

Feed Name/Description	IFN[b]		DM[c] (%)	Ca (%)	P (%)	Bio-avail P (%)	Mg (%)	K (%)	Na (%)	Cl (%)	S (%)	Cu (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	Se (mg/kg)	Zn (mg/kg)
Ingredients of animal origin																
Bacon																
Pork, cured			68.40	0.01	0.14		0.01	0.15	0.73			0.64	6.00	0.00	0.25	12.00
		N	251	2	20		0	15	20			18	20	18	14	19
Beef																
Meat, mechanically separated			40.60	0.49	0.32		0.02	0.28	0.06			0.56	57.00	0.00	0.21	36.00
		N	56	55	28		1	1	1			20	36	1	1	47
Broth (or bouillon), dehydrated			96.70	0.06	0.32		0.05	0.45	16.98			0.00	10.00	5.00	0.28	
		N	3	1	2		2	2	3			1	1	3	1	1
Heart, raw			24.40	0.00	0.17		0.02	0.27	0.06			3.61	46.00	0.00	0.22	24.00
		N	15	7	7		7	7	11			8	10	2	3	38
Kidney, raw			23.00	0.01	0.21		0.02	0.26	0.18			4.69	74.00	1.00	1.49	19.00
		N	28	9	9		9	8	8			509	13	231	9	251
Liver, raw			31.00	0.01	0.32		0.02	0.32	0.07			33.39	68.00	3.00	0.41	39.00
		N	50	1	10		13	10	9			311	33	232	6	293
Tripe, raw			18.60	0.01	0.08		0.01	0.27	0.05			0.90	20.00	0.00	0.46	25.00
		N	6	1	1		1	1	1			1	4	1	1	10
Chicken																
Meat and skin, raw			38.20	0.01	0.17		0.02	0.20	0.07			0.74	10.00	0.00	0.14	12.00
		N	1	1	1		1	1	1			1	1	1	1	1
Broth (or bouillon), dehydrated			97.70	0.19	0.17		0.06	0.31	18.59			0.00	10.00	2.00	0.28	1.00
		N	4	1	2		2	1	3			1	1	1	1	1
Gizzard			23.80	0.01	0.14		0.02	0.24	0.08			0.96	35.00	1.00	0.56	0.00
		N	13	10	10		10	10	10			10	10	10	1	8
Liver			26.40	0.01	0.27		0.02	0.23	0.08	0.00		3.95	86.00	3.00	0.64	31.00
		N	18	10	10		10	10	10	10		20	10	10	6	8
Egg																
Dried, whole			96.60	0.22	0.82		0.04	0.49	0.52			1.96	68.00	1.00	1.20	53.00
		N	3	3	3		2	2	2			2	2	2	1	2
Fish																
Meal, menhaden	5-02-009		91.20	4.87	2.78	2.61	0.18	0.68	0.62	0.75	1.04	6.41	518.00	29.00	2.06	102.00
		N	136	113	112		64	66	67	3	35	65	66	66	31	63
Meal, tuna	5-02-023		93.00	8.40	4.20	4.20	0.30	0.40	0.70			6.00	650.00	10.00	4.00	240.00
		N	1	1	1	1	1	1	1			1	1	1	1	1
Meal, white	5-02-025		91.00	7.16	3.66	3.50	0.20	0.97	0.88	0.50	0.48	7.00	131.00	11.00	1.56	85.00
		N	2	2	2	1	2	2	2	2	1	2	2	2	2	2
Lamb																
Ground			40.50	0.02	0.16		0.02	0.22	0.06			1.01	16.00	0.00	0.19	34.00
		N	1	1	1		1	1	1			1	1	1	1	1
Liver			28.60	0.01	0.36		0.02	0.31	0.07			69.79	74.00	2.00	0.82	47.00
		N	17	1	1		1	1	1			520	1	13	13	8
Meat, mechanically separated			41.30	0.16	0.34		0.02	0.29	0.06			0.58	59.00	0.00	0.20	37.00
		N	5	5	1		1	1	1			1	1	1	1	1

Meat																
	Meal, rendered	5-09-323		93.90	8.31	3.94		0.25	0.46	0.75	0.66	0.48	19.56	655.00	23.00	0.42	106.00
			N	79	63	63		63	63	63	2	30	63	63	11	35	11
	Meal, with bone, rendered	5-00-388		94.00	9.97	4.46		0.24	0.97	0.67	0.51	0.38	9.26	564.00	21.00	0.25	88.00
			N	63	52	52		52	52	52	3	14	52	52	52	1	52
Poultry																	
	By-product meal	5-03-798		93.50	3.50	2.05		0.21	0.58	0.35	0.55	0.51	14.00	470.00	11.00	0.78	120.00
			N	2	2	2		2	2	2	2	2	2	2	2	2	2
Shrimp																	
	Meat, mixed species			24.10	0.05	0.21		0.04	0.19	0.15			2.64	24.00	1.00	0.38	11.00
			N	212	117	112		6	27	26			285	8	1	15	275
Milk																	
	Skimmed, dried	5-01-175		92.50	1.27	1.01	1.00	0.12	0.84	0.52	0.90	0.32	11.75	29.00	2.00	0.12	39.00
			N	2	2	2	1	2	2	2	1	2	2	2	2	2	1
Turkey																	
	Mechanically deboned			30.90	0.15	0.12		0.01	0.17	0.05			0.93	16.00	0.00	0.27	29.00
			N	21	6	1		1	1	1			1	6	1	1	6
Whey																	
	Dried	4-01-182		93.50	0.92	0.78	0.79	0.13	1.13	1.30	1.50	1.04	44.55	145.00	7.00	0.07	3.00
			N	2	2	2	1	2	2	2	2	2	2	2	2	2	2
Ingredients of plant origin																	
Barley																	
	Grain	4-00-549		90.20	0.04	0.29	0.15	0.13	0.46	0.01	0.15	0.15	5.28	40.00	19.00	0.15	28.00
			N	9	18	11	1	18	18	17	2	2	27	21	23	2	30
Beet (sugar)																	
	Pulp, dried	4-00-669		88.30	0.80	0.08		0.20	0.84	0.27	0.15	0.26	9.74	564.00	55.00	0.12	19.00
			N	200	172	154		154	154	154	18	57	154	154	154	11	154
Carrots																	
	Whole, raw			12.20	0.03	0.04		0.02	0.32	0.04			0.47	5.00	1.00	0.01	2.00
			N	238	236	237		237	239	243			90	241	229	6	222
Cereal																	
	Cereal by-product	4-00-466		88.50	0.15	0.26	0.18	0.09	0.29	0.53	0.72	0.09	3.57	219.00	24.00	0.40	70.00
			N	62	49	49	1	49	49	49	6	25	49	49	49	1	49
Chicory																	
	Root			20.00	0.04	0.06		0.02	0.29	0.05			0.77	0.00	2.00	0.01	3.00
			N	1	1	1		1	1	1			1	1	1	1	1
Corn, yellow																	
	Bran, crude			95.30	0.04	0.07		0.06	0.04	0.01			2.48	28.00	1.00	0.17	16.00
			N	6	5	4		5	5	5			5	3	2	1	5
	Distillers grain, dried	5-02-842		94.00	0.09	0.41	0.17	0.20	0.16	0.47	0.07	0.43	30.00	300.00	23.00	0.35	55.00
			N	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Distillers grain w/ solubles, dried	5-02-843 and 5-28-236		90.20	0.20	0.75	0.40	0.30	0.99	0.27	0.23	0.40	7.28	161.00	24.00	0.35	59.00
			N	893	650	650	1	649	649	648	91	279	649	266	649	13	649
	Gluten feed, dried	5-28-243 and 5-02-903		89.40	0.06	0.89	0.22	0.38	1.31	0.12	0.19	0.39	5.57	177.00	21.00	0.17	67.00
			N	132	145	145	1	145	145	84	3	66	145	145	145	13	145

TABLE 13-6 (continued)

Feed Name/Description		IFN[b]		DM[c] (%)	Ca (%)	P (%)	Bio-avail P (%)	Mg (%)	K (%)	Na (%)	Cl (%)	S (%)	Cu (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	Se (mg/kg)	Zn (mg/kg)
	Gluten meal	5-28-242		86.50	0.05	0.52		0.12	0.40	0.04	0.07	0.73	3.84	124.00	13.00	0.35	42.00
			N	67	57	58		58	58	58	2	24	58	58	58	12	58
	Grits			90.00	0.00	0.07		0.03	0.14	0.00			0.75	10.00	1.00	0.17	4.00
			N	157	1	1		1	22	154			4	1	4	1	4
	Grain	4-02-935		89.30	0.01	0.23	0.09	0.11	0.30	0.03	0.04	0.08	3.11	29.00	6.00	0.13	21.00
			N	12	6	7	1	3	3	3	2	2	8	8	5	7	7
	Meal, degermed			88.40	0.01	0.08		0.04	0.16	0.00			0.78	11.00	1.00	0.08	7.00
			N	513	8	8		8	24	114			23	1	3	13	27
	Meal, whole kernel			89.70	0.01	0.24		0.13	0.29	0.04			1.93	35.00	5.00	0.16	18.00
			N	10	9	3		6	6	6			6	9	3	1	6
	Starch			91.70	0.00	0.01		0.00	0.00	0.01			0.50	5.00	1.00	0.03	1.00
			N	5	7	3		7	7	4			2	6	3	8	6
	Syrup, dark			77.20	0.02	0.01		0.01	0.04	0.16			0.53	4.00	1.00	0.01	0.00
			N	5	1	1		1	1	2			5	1	5	1	5
Flaxseed (linseed)																	
	Whole			92.20	0.20	0.50		0.36	0.70	0.03			10.41	62.00	33.00	0.06	42.00
			N	3	6	6		5	6	5			5	5	5	5	5
Molasses																	
	Beet, sugar	4-00-668		78	0.12	0.02		0.23	4.73	1.15	1.30	0.47	17.20	71.00	46.00		14.00
			N	22	14	12		11	11	9	1	10	8	9	8		5
Oats																	
	Grain	4-03-309		90.00	0.10	0.36		0.14	0.47	0.03	0.11	0.17	7.20	95.00	39.00	0.43	37.00
			N	177	222	229		206	205	102	1	31	184	185	194	69	197
	Groats	4-03-331		92.00	0.07	0.45	0.17	0.09	0.34	0.05		0.20	6.40	35.00	29.00		
			N	1	1	1	1	1	1	1		1	1	1	1		
Peas																	
	Green, raw			21.10	0.03	0.11		0.03	0.24	0.01			1.76	15.00	4.00	0.02	12.00
			N	10	8	8		8	10	7			7	8	7	1	7
Potato																	
	Flesh and skin, raw			8.00	0.01	0.06		0.02	0.44	0.01			1.08	10.00	2.00	0.00	3.00
			N	9	9	9		9	9	9			9	9	9	299	9
Rice																	
	Bran	4-03-928		90.60	0.06	1.61		0.74	1.43	0.03	0.08	0.17	9.13	216.00	172.00	0.18	64.00
			N	73	70	70		62	67	55	3	27	58	58	24	9	56
	Brewers (broken)	4-03-932		89.00	0.08	0.08		0.11	0.13	0.07	0.08	0.06			18.00	0.27	17.00
			N	1	1	1		1	1	1	1	1			1	1	1
	Brown, medium grain			87.60	0.03	0.26		0.14	0.27	0.00			2.77	18.00	37.00		20.00
			N	4	1	3		1	4	1			1	5	1		1
	Flour, brown			88.00	0.01	0.34		0.11	0.29	0.01			2.30	20.00	40.00		25.00
			N	3	3	3		3	3	3			2	2	3		3
	Flour, white			88.10	0.01	0.10		0.04	0.08	0.00			1.30	4.00	12.00	0.15	8.00
			N	2	2	2		2	2	2			2	2	2	2	2
	Hulls	1-08-075		92.00	0.04	0.10			0.40	0.08	0.07	0.08					
			N	1	1	1			1	1	1	1					

Sorghum																
	Grain	4-20-893		87.00	0.04	0.30		0.15	0.35	0.01	0.09	0.08	10.00	45.00	15.00	0.20	15.00
			N	1	1	1		1	1	1	1	1	1	1	1	1	1
Soybean																	
	Flour, defatted			92.80	0.24	0.67		0.29	2.38	0.02			40.65	92.00	30.00	17.00	25.00
			N	6	17	11		13	13	13			14	13	13	1	14
	Flour, full fat, roasted			96.20	0.19	0.48		0.37	2.04	0.01			22.21	58.00	21.00	0.08	36.00
			N	58	1	1		1	1	1			1	1	1	1	1
	Hulls	1-04-560		90.90	0.57	0.15		0.23	1.37	0.01	0.05	0.11	9.09	549.00	24.00	0.19	32.00
			N	131	82	80		73	72	75	5	37	72	73	74	4	73
	Meal, solvent, (44% CP)	5-20-637 and 5-04-604		89.10	0.35	0.63		0.28	1.98	0.03	0.08	0.41	19.75	162.00	31.00	0.19	50.00
			N	12	27	30		20	22	13	2	7	16	16	16	43	14
	Meal, solvent, without hulls (48% CP)	5-20-638 and 5-04-612		89.50	0.31	0.63		0.26	2.16	0.03	0.12	0.35	14.32	184.00	36.00	0.12	52.00
			N	562	257	257		244	247	238	97	143	244	238	238	35	238
Sugar																	
	Granulated			100.00	0.00	0.00		0.00	0.00	0.00			0.43	1.00	0.00	0.01	0.00
			N	9	19	12		24	21	12			16	23	18	2	17
	Brown			98.40	0.09	0.02		0.03	0.35	0.04			2.98	19.00	3.00	0.01	2.00
			N	5	6	4		6	6	6			6	6	7	4	6
Wheat																	
	Flour, whole grain			89.70	0.03	0.00		0.14	0.41	0.01			3.82	39.00	38.00	0.71	29.00
			N	15	8	8		6	7	7			11	8	10	3	11
	Germ			88.90	0.04	0.84		0.24	0.89	0.01			7.96	63.00	133.00	0.79	123.00
			N	10	6	6		6	6	6			6	7	9	1	6
	Germ meal	5-05-218		89.00	0.01	1.00	0.31	0.22	0.90	0.02	0.08	0.31	10.00	41.00	100.00	0.60	115.00
			N	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Flour, white, unenriched			88.10	0.02	0.11		0.02	0.11	0.00			1.44	12.00	7.00	0.34	7.00
			N	72	113	47		129	94	82			49	1	48	46	136
	Middlings	4-05-205		89.50	0.14	0.91		0.37	1.23	0.03	0.09	0.16	9.00	141.00	112.00	0.45	82.00
			N	294	196	197		182	183	171	17	59	176	178	176	10	172
	Mill run			90.00	0.10	1.02		0.47									
			N	1	1	1		1									
Yeast																	
	Brewers, Torula, dried	7-05-534		93.00	0.54	1.64	0.45	0.13	1.79	0.09	0.10	0.32	13.70	95.00	13.00	1.00	99.00
			N	2	2	2	1	2	2	2	2	2	2	2	2	2	2

[a]For each ingredient two numbers are given: the first is the percent composition of each respective amino acid in the ingredient; the second, the number (*N*) of observations on which the data are based.
[b]International Feed Number.
[c]Dry matter.

TABLE 13-7 Vitamin Content of Selected Ingredients (mg/kg, as fed)[a]

Feed Name	Description	IFN[b]		Biotin (mg/kg)	Choline (mg/kg)	Folate (mg/kg)	Niacin (mg/kg)	Pantothenic Acid (mg/kg)	Riboflavin (mg/kg)	Thiamin (mg/kg)	B_6 (mg/kg)	B_{12} (mg/kg)	Carotene (mg/kg)	Vit E (mg/kg)
Ingredients of animal origin														
Bacon														
	Pork, cured					0.02	28.00	3.50	1.00	3.70	1.40	0.01		4.90
			N			7	18	6	18	18	18	15		1
Beef														
	Meat, mechanically separated					0.05	25.00	2.80	1.20	0.70	2.90	0.03		
			N			1	1	1	1	1	1	1		
	Broth (or bouillon), dehydrated					0.32	45.00	3.00	2.40	0.70	2.00	0.01		2.40
			N			1	2	1	2	1	1	1		1
	Heart, raw					0.02	95.00	23.20	10.20	1.90	4.30	0.14		2.00
			N			1	1	1	1	1	2	2		1
	Kidney, raw					0.80	80.00	36.40	25.50	3.80	5.10	0.27		2.00
			N			4	1	2	1	2	3	2		1
	Liver, raw					2.48	128.00	76.20	27.80	2.60	9.40	0.69		6.70
			N			9	3	2	3	2	4	9		1
	Tripe, raw					0.02	1.00	5.60	1.70	0.10	0.40	0.02		0.80
			N			1	1	1	3	6	1	1		1
Chicken														
	Meat and skin, raw					0.06	63.00	9.20	1.70	1.10	3.30	0.00		
			N			1	1	1	1	1	1	1		
	Broth (or bouillon), dehydrated					0.32	25.00	6.00	4.30	1.00	1.00	0.00		1.10
			N			1	2	1	2	1	1	1		1
	Gizzard					0.52	47.00	7.50	1.90	0.30	1.40	0.02		11.90
			N			3	8	1	8	8	6	2		1
	Liver					7.38	93.00	61.80	19.60	1.40	7.60	0.23		14.40
			N			3	8	6	10	8	7	4		1
Egg														
	Dried, whole					1.71	3.00	59.10	15.40	2.00	3.90	0.04		43.80
			N			2	2	2	2	2	2	2		1
Fish														
	Meal, menhaden	5-02-009		0.15	3080.00	1.00	55.00	8.80	4.80	0.20		0.15		5.70
			N	1	1	1	1	1	1	1		1		1
	Meal, tuna	5-02-023			3050.00		65.00	8.80	8.80			0.14		5.60
			N		1		1	1	1			1		1
	Meal, white	5-02-025		0.80	3575.00	0.30	49.00	7.30	6.90	1.60	5.90	0.08		7.30
			N	1	2	1	2	2	2	2	1	2		2
Lamb														
	Ground					0.18	60.00	6.50	2.10	1.10	1.30	0.02		2.00
			N			1	1	1	1	1	1	1		1
	Liver					2.30	161.00	61.30	36.30	3.40	9.00	0.90		
			N			4	1	1	1	1	1	19		
	Meat, mechanically separated					0.05	25.00		1.20	0.70	1.10	0.03		
			N			1	1		1	1	1	1		
Meat														
	Meal, rendered	5-09-323		0.14	2200.00	0.60	59.00	5.80	5.20	0.20		0.09		
			N	1	1	1	1	1	1	1		1		
	Meal, with bone, rendered	5-00-388		0.14	1996.00	0.30	46.00	4.10	4.40	0.80	12.80	70.00		1.00
			N	1	1	1	1	1	1	1	1	1		1

Poultry														
	By-product meal	5-03-798		0.30	5966.00	1.00	40.00	10.60	10.50	1.00	4.40	0.31		2.10
			N	1	2	1	2	2	2	1	1	2		2
Shrimp														
	Meat, mixed species					0.03	26.00	2.80	0.30	0.30	1.00	0.01		8.20
			N			1	6	2	6	5	3	19		1
Milk														
	Skimmed, dried	5-01-175		0.33	1322.00	0.62	12.00	35.80	20.60	3.50	0.40	0.03		9.00
				2	2	2	2	2	2	2	1	2		1
Turkey														
	Mechanically deboned					0.07	20.00	6.70	1.30	0.50	2.10	0.00		
			N			1	1	1	1	1	1	1		
Whey														
	Dried	4-01-182		0.37	1675.00	0.90	11.00	45.90	28.50	3.90	4.00	0.02		0.20
			N	2	2	1	2	2	2	2	1	2		1
Ingredients of plant origin														
Barley														
	Grain	4-00-549		0.18	1009.00	0.20	53.00	5.70	2.40	5.00	3.10	0.00		20.70
			N	2	2	8	3	3	4	4	4	1		3
Beet (sugar)														
	Pulp, dried	4-00-669			809.00		19.00	1.10	0.90	0.30	1.90	0.00	5.00	13.20
			N		2		2	2	2	2	1	1	2	1
Carrots														
	Whole, raw					0.14	9.00	2.00	0.60	1.00	1.50	0.00		4.60
			N			9	23	11	177	179	21	1		1
Cereal														
	Cereal by-product	4-00-466		1230.00	0.15	18.00	14.50	1.50	1.50			5.00	25.00	
			N		1	1	1	1	1	1			1	1
Chicory														
	Root					0.23	4.00	3.20	0.30	0.40	2.40	0.00		
			N			1	1	1	1	1	1	1		
Corn, yellow														
	Bran, crude					0.04	27.00	6.40	1.00	0.10	1.50	0.00		23.20
			N			4	4	4	6	5	4	1		1
	Distillers grain, dried	5-02-842		0.40	1850.00	0.00	42.00	5.90	2.80	1.60			2.00	30.50
			N	1	1	1	1	1	1	1			1	1
		5-02-843 and												
	Distillers grain w/ solubles, dried	5-28-236	*N*	0.30	3400.00	0.88	80.00	11.40	9.00	3.50			4.00	40.00
			N	1	1	1	1	1	1	1			1	1
		5-28-2433 and												
	Gluten feed, dried	5-02-903		0.22	2420.00	0.20	75.00	17.80	2.40	2.00			8.00	14.80
			N	1	1	1	1	1	1	1			1	1
	Gluten meal	5-28-242		0.15	330.00	0.20	55.00	3.00	2.20	0.30	6.20			24.00
			N	1	1	1	1	1	1	1	1			1
	Grits					0.05	12.00	4.90	0.40	1.30	1.50	0.00		2.60
			N			3	1	1	1	1	1	1		1

TABLE 13-7 (continued)

Feed Name	Description	IFN[b]		Biotin (mg/kg)	Choline (mg/kg)	Folate (mg/kg)	Niacin (mg/kg)	Pantothenic Acid (mg/kg)	Riboflavin (mg/kg)	Thiamin (mg/kg)	B_6 (mg/kg)	B_{12} (mg/kg)	Carotene (mg/kg)	Vit E (mg/kg)
	Grain	4-02-935		0.07	860.00	0.24	27.00	4.00	1.40	3.30	6.50	0.00	2.00	17.20
			N	2	2	3	3	3	3	3	3	1	1	3
	Meal, degermed					0.48	10.00	3.10	0.50	1.40	2.60	0.00		3.30
			N			23	1	25	1	1	5	1		1
	Meal, whole kernel					0.25	36.00	4.30	2.00	3.90	3.00	0.00		6.70
			N			1	8	6	9	8	3	1		1
	Starch					0.00		0.00	0.00	0.00	0.00	0.00		0.00
			N			1	1	1	1.0	1	1	1		1
	Syrup, dark					0.00	0.00	0.20	0.10	0.10	0.10	0.00		0.00
			N			2	2	2	2	2	2	1		1
Flaxseed (linseed)														
	Whole					2.78	14.00	15.30	1.60	1.70	9.30	0.00		50.00
			N			1	1	1	1	1	1	1		1
Molasses														
	Beet, sugar	4-00-608					48.00	4.60	2.40					
			N				1	1	1					
Oats														
	Grain	4-03-309		0.27	946.00	0.30	12.00	7.80	1.10	6.00	1.00			20.00
			N	1	1	1	1	1	1	1	1			1
	Groats	4-03-331		0.20	1232.00	0.30	18.00	11.00	1.30	6.80				15.00
			N	1	1	1	1	1	1	1				1
Peas														
	Green, raw					0.65	21.00	1.00	1.30	2.70	1.70	0.00		3.90
			N			1	7	1	7	7	7	1		1
Potato														
	Flesh and skin, raw					0.28	14.00	3.70	0.20	0.70	1.80	0.00		0.20
			N			9	9	9	8	9	9	1		1
Rice														
	Bran	4-03-928		0.42	1135.00	2.20	293.00	23.00	2.50	22.50	14.00			60.00
			N	1	1	1	1	1	1	1	1			1
	Brewers (broken)	4-03-932		0.08	800.00	0.20	30.00	8.00	0.70	1.40	28.00			14.00
			N	1	1	1	1	1	1	1	1			1
	Brown, medium grain					0.20	43.00	14.90	0.40	4.10	5.10	0.00		6.60
			N			1	5	1	5	5	1	1		1
	Flour, brown					0.16	63.00	15.90	0.80	4.40	7.40	0.00		7.20
			N			6	3	3	3	3	3	1		1
	Flour, white					0.04	26.00	8.20	0.20	1.40	4.40	0.00		1.30
			N			2	2	2	2	2	2	1		1
	Hulls	1-08-075												
			N											
Sorghum														
	Grain	4-20-893		0.26	668.00	0.20	41.00	12.40	1.30	3.00	5.20			7.00
			N	1	1	1	1	1	1	1	1			1

Soybean												
	Flour, defatted					3.05	26.00	20.00	2.50	7.00	5.70	0.00	
			N			7	5	5	5	5	5	1	
	Flour, full fat, roasted					2.27	33.00	12.10	9.40	4.10	3.50	0.00	
			N			1	1	1	1	1	1	1	
	Hulls	1-04-560											
			N										
	Meal, solvent (44% CP)	5-20-637 and 5-04-604		0.32	2794.00	1.30	29.00	16.00	2.90	4.50	6.00		2.00
			N	1	1	1	1	1	1	1	1		1
	Meal, solvent, without hulls (48% CP)	5-20-638 and 5-04-612		0.32	2731.00	1.30	22.00	15.00	2.90	3.20	5.00		3.00
			N	1	1	1	1	1	1	1	1		1
Sugar													
	Granulated					0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00
			N			3	3	3	3	1	3	1	1
	Brown					0.01	1.00	1.10	0.10	0.10	0.30	0.00	0.00
			N			2	5	5	4	5	5	1	1
Wheat													
	Flour, whole grain					0.44	64.00	10.10	2.20	1.20	3.40	0.00	12.30
			N			7	8	2	20	20	3	1	1
	Germ					2.81	68.00	22.60	5.00	18.80	13.00	0.00	
			N			10	7	6	7	7	7	1	
	Germ meal	5-05-218			3175.00	2.80		23.20	6.10	21.90			133.00
			N		1	1	0	1	1	1		0	1
	Flour, white, unenriched					0.26	13.00	4.40	0.40	1.20	0.40	0.00	0.60
			N			15	1	10	1	1	45	1	1
	Middlings	4-05-205		0.37	1439.00	0.80	98.00	13.00	2.20	16.50	9.00		40.00
			N	1	1	1	1	1	1	1	1		1
	Mill run												
			N										
Yeast													
	Brewers, Torula, dried	7-05-534		1.25	2871.00	11.86	498.00	78.00	55.80	6.20	36.30	0.00	
			N	2	2	2	2	2	2	2	1	1	

[a]For each ingredient two numbers are given: the first is the percent composition of each respective amino acid in the ingredient; the second, the number (N) of observations on which the data are based.
[b]International Feed Number.

TABLE 13-8 Composition of Selected Inorganic Macro-mineral Sources Used in Petfood

Mineral Source	IFN[a]	Calcium %	Phosphorus %	Sodium %	Potassium %	Chloride %	Magnesium %
Ammonium chloride	8-08-814	—	—	—	—	66.28	—
Ammonium phosphate, monobasic	6-09-338	—	24.74	—	—	—	—
Ammonium phosphate, dibasic	6-00-370	—	20.60	—	—	—	—
Bone meal, steamed	6-00-400	30.71	12.86	5.69	—	—	—
Calcium carbonate	6-01-069	39.39	—	—	—	—	—
Calcium chloride, anhydrous	6-20-774	36.11	—	—	—	63.89	—
Calcium chloride, dihydrate	N/A	27.53	—	—	—	48.23	—
Calcium hydroxide	6-14-014	54.09	—	—	—	—	—
Calcium oxide	6-14-003	71.47	—	—	—	—	—
Calcium phosphate, dibasic	6-01-080	22.00	19.30	—	—	—	—
Calcium phosphate, monobasic	6-01-082	16.40	24.60	—	—	—	—
Limestone, ground	6-02-635	34.00	—	—	—	—	2.06
Magnesium carbonate	6-02-754	—	—	—	—	—	30.81
Magnesium chloride, hexahydrate	6-20-872	—	—	—	—	34.88	11.96
Magnesium oxide	6-02-756	—	—	—	—	—	56.20
Magnesium sulfate	6-02-758	—	—	—	—	—	9.80
Oystershell flour	6-03-481	38.00	—	—	—	—	—
Phosphate, defluorinated	6-01-780	32.00	18.00	4.90	—	—	—
Phosphoric acid (H_3PO_4)	6-03-707	—	31.60	—	—	—	—
Potassium bicarbonate	6-29-493	—	—	—	39.05	—	—
Potassium carbonate	6-09-336	—	—	—	56.58	—	—
Potassium chloride	6-03-755	—	—	1.00	57.00	47.30	—
Potassium iodide	6-03-759	—	—	—	21.00	—	—
Potassium sulfate	6-06-098	—	—	—	41.84	—	—
Sodium bicarbonate	6-04-272	—	—	27.00	—	—	—
Sodium carbonate	6-12-316	—	—	—	—	—	—
Sodium chloride	6-04-152	—		39.34	—	60.66	—
Sodium phosphate, monobasic	6-04-288	—	22.50	16.68	—	—	—
Sodium selenate, decahydrate	6-26-014	—	—	12.46	—	—	—
Sodium selenite	6-26-013	—	—	26.60	—	—	—
Sodium sulfate, decahydrate	6-04-292	—	—	14.27	—	—	—

[a]International Feed Number.

TABLE 13-9 Composition of Selected Inorganic Micro-mineral Sources Used in Petfood

Mineral Source	Chemical Formula	IFN[a]	Copper (mg/kg)	Iodine (mg/kg)	Iron (mg/kg)	Manganese (mg/kg)	Selenium (mg/kg)	Zinc (mg/kg)	Cobalt (mg/kg)
Calcium iodate	$Ca(IO_3)_2$	6-16-610	—	651,000	—	—	—	—	—
Cobalt carbonate	$CoCO_3$	6-01-566	—	—	—	—	—	—	450,000
Cobalt sulfate, heptahydrate	$CoSO_4 \cdot 7H_2O$	6-01-564	30	—	10	20	—	—	210,000
Cupric carbonate	$CuCO_3$	6-01-703	530,000	—	—	—	—	—	—
Cupric chloride, dihydrate	$CuCl_2 \cdot 2H_2O$	6-01-705	372,000	—	—	—	—	—	—
Cupric oxide	CuO	6-01-711	798,800	—	—	—	—	—	—
Cupric sulfate, pentahydrate	$CuSO4 \cdot 5H_2O$	6-01-720	254,500	—	—	—	—	—	—
Cuprous iodide	CuI	6-01-721	333,600	666,400	—	—	—	—	—
Cuprous oxide	Cu_2O	6-28-224	888,200	—	—	—	—	—	—
Ferrous carbonate	$FeCO_3$	6-01-863	3,000	—	430,000	3,500	—	—	—
Ferrous sulfate, heptahydrate	$FeSO_4 \cdot 7H_2O$	6-20-734	—	—	210,000	1,200	—	100	—
Manganese carbonate	$MnCO_3$	6-03-036	—	—	—	478,000	—	—	—
Manganese chloride	$MnCl_2 \cdot$	6-03-038	—	—	—	430,000	—	—	—
Manganese oxide	MnO	6-03-056	2,000	—	34,000	600,000	—	—	—
Manganese sulfate, monohydrate	$MnSO_4 \cdot H_2O$	N/A	—	—	400	325,069	—	—	—
Manganese sulfate, pentahydrate	$MnSO^4 \cdot 5H_2O$	N/A	—	—	—	227,891	—	—	—
Potassium iodide	KI	6-03-759	—	681,700	—	—	—	—	—
Sodium selenate, decahydrate	$Na_2SeO_4 \cdot 10H_2O$	6-26-014	—	—	—	—	213,920	—	—
Sodium selenite	Na_2SeO_3	6-26-013	—	—	—	—	456,000	—	—
Zinc carbonate	$ZnCO_3$	6-05-549	—	—	—	—	—	521,400	—
Zinc chloride	$ZnCl_2$	6-05-551	—	—	—	—	—	479,700	—
Zinc oxide	ZnO	6-05-533	—	—	—	—	—	780,000	—
Zinc sulfate, monohydrate	$ZnSO_4 \cdot H_2O$	6-05-555	—	—	—	—	—	363,600	—

[a]International Feed Number.

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14

Other Food Constituents

CONSTITUENTS INTENDED FOR NUTRITIVE VALUE

Introduction

In the years since the previous editions of nutrient requirements for dogs and cats were published (National Research Council, 1985, 1986), there has been an increase of interest in substances in the diet that may affect the structure or function of the body, but whose absence from the diet does not fit into classical models of nutritional deficiency. Many of these substances play vital roles in the normal metabolism of the animal, but cannot be deemed essential because the body is capable of synthesizing them from other dietary components. Still, it is thought that their inclusion in the diet will augment endogenous production and facilitate bodily functions. Other substances that may play a role in the normal function of the body must come from an exogenous source, but determinations of essentiality have yet to be established. For still other compounds added to dog and cat foods, their roles in normal metabolism are unknown and likely nonexistent.

A few of these substances fall into established categories of nutrients and are discussed in detail elsewhere in this report (e.g., omega-3 fatty acids, "prebiotic" fibers, some vitamins and trace minerals). The remainder do not fit as neatly into the preceding chapters. While the nature and functions of these substances are broad in scope, only a few of the more commonly used compounds are discussed here.

Under the Dietary Supplement Health and Education Act of 1994 (DSHEA), most of these substances are allowed in dietary supplement products for human consumption without demonstration of safety and utility prior to marketing. However, since DSHEA has been determined by the U.S. Food and Drug Administration (FDA) as inapplicable to products intended for animals, many of these same substances may be considered unapproved food additives when used in dog or cat formulations. Thus, a pet product containing these substances might be subject to regulatory action as an adulterated food. In addition, claims that a substance can treat, prevent, cure, or mitigate a disease or condition (except for prevention, but not treatment, of an essential nutrient deficiency) or affect the structure or function of the body in a manner distinct from its provision of "nutritive value" may render it a "drug" under the law. Further, it could be considered an adulterated drug unless it has undergone sufficient review to establish safety and efficacy for its intended use prior to marketing. Therefore, even if a particular substance is allowed in a dog or cat food product, the manufacturer may be restricted in terms of statements regarding its function in the food, including some of the functions described below.

Chondroprotective Agents

The most commonly used chondroprotective agents in dog and cat foods are glucosamine and chondroitin sulfate. Glucosamine is an amino sugar that can be synthesized in the body from other dietary components. It is used by the body in the further synthesis of glycosaminoglycans (GAGs), which are substances associated with cartilage and joint tissues. It also stimulates production of GAGs and inhibits degradative enzymes. Chondroitin sulfate is a form of GAG that consists of a long carbohydrate polymer associated with a small amount of protein. In addition to functions similar to glucosamine, it also holds water in the cartilage tissue, which assists in the delivery of nutrients and serves as a shock absorber for the joints.

Commercially, glucosamine is derived from the hydrolysis of chitin, a material found in the shells of crabs and shrimp. It is most often available in the hydrochloride form but may also be found in a sulfated form. Chondroitin sulfate is typically extracted from the cartilaginous tissue of cattle and swine. Unpublished data suggest that other pet-food ingredients that may contain appreciable amounts of chondroitin sulfate or other GAGs include meat and poultry meals.

Glucosamine and GAGs can be wholly synthesized in the body from other nutritive components of the diet. Thus, they are not considered dietary essential nutrients. Because of their modes of action, the premise of their inclusion in the diet is to augment their endogenous production in animals that may be susceptible to osteoarthritic conditions (especially older animals, large- and giant-breed dogs, and working dogs).

One form of GAG is approved for the treatment of osteoarthritic conditions in horses and dogs. However, this is in the form of an injectable drug only, and orally administered agents have not received similar approval to date. Although research has shown glucosamine to be absorbable by the gastrointestinal tract of dogs, some question whether the same is true for larger molecules such as chondroitin sulfate (Senikar et al., 1986). Later work has demonstrated significant absorption of low-molecular-weight chondroitin sulfate after multiple oral doses in dogs and an increase in concentration of epitopes of chondroitin sulfate in synovial fluid after oral administration (Johnson et al., 2001; Adebowale et al., 2002). Some degree of clinical benefit of orally administered chondroprotective agents, particularly glucosamine hydrochloride and chondroitin sulfate in combination, has been shown in dogs (Lippiello et al., 1998; Anderson et al., 1999; Canapp et al., 1999). Many of these benefits are relatively short-term and based on subjective assessment of pain and mobility in the test subjects.

Other substances that have been characterized as chondroprotective include green-lipped mussel extract and methylsulfonylmethane (MSM). Green-lipped mussel extract consists of a mixture of GAGs, omega-3 fatty acids, and other compounds that, in combination, are reported to benefit dogs exhibiting chronic lameness (Bui and Bierer, 2001). However, a subsequent study failed to confirm that finding (Dobenecker et al., 2002). The reported benefit of MSM is different in that it is intended as a source of bioavailable sulfur (Parcell, 2002). Sulfur is a component of compounds associated with joint structure and function such as glucosamine. Studies of the effects of MSM in dogs or cats have not been reported.

Definitive, long-term safety studies of chondroprotective agents in dogs and cats have not been reported. Potential adverse effects include disruption of normal clotting mechanisms (heparin is also a GAG). Short-term experiments indicate little risk of adverse effects, including effects on blood clotting, at typical ingestion levels of glucosamine or chondroitin sulfate in the dog or cat (McNamara et al., 1996, 2000). In vitro studies on cell cultures are mixed as to whether dietary supplementation of glucosamine may enhance or actually impair endogenous production (Kim and Conrad, 1974; Anderson et al., 1999).

Studies have indicated that glucosamine may also induce or exacerbate insulin resistance (Kajinuma et al., 1975; Robinson et al., 1993; Almada et al., 2000; Monauni et al., 2000). This suggests a possible contraindication for use in dogs with type II diabetes mellitus or those at risk for the disease (e.g., obese dogs). However, a recent study failed to demonstrate adverse effects of glucosamine or chondroitin sulfate on glucose metabolism (Echard et al., 2001).

Finally, since GAGs may come from various species of animal and be accompanied by other proteins, there is a potential for allergic reactions (especially when the source of the GAG is not known). In light of all these possible concerns, although chondroprotective agents may be used for selected individual animals, their widespread inclusion in the diets of healthy populations may not be warranted at this time.

Antioxidants

General Principles

Antioxidants include a host of substances that vary in structure, specific function, and site of function in the body. All act to prevent oxidative damage to nutrients and other compounds in the body and to inhibit or quench the formation of free radicals. Free radicals are defined as compounds containing at least one unmatched electron. They are produced as a result of normal metabolism but can also be unpaired through exposure to environmental stressors such as UV radiation, pollutants, tobacco smoke, and other chemical agents.

Free radicals are highly reactive and subsequently destroy other molecules to form even more free radicals. The effect of this continuing process is thought to be integral to the pathogenesis of many conditions, including cancer, arthritis, cardiovascular disease, other degenerative conditions, and even the aging process itself. The immune system appears especially susceptible to damage. Because oxygen is essential to life, oxidative damage and free-radical formation cannot be prevented entirely. Also, once damage has been done, it cannot be wholly reversed. However, antioxidants can curtail the process somewhat.

Vitamin E

Vitamin E serves mainly to protect the lipid-rich cell membrane by preventing oxidation of polyunsaturated fats. Failure to prevent oxidation can result in loss of membrane integrity and cell rupture. Vitamin E cannot be synthesized by the body. For this reason, it is considered a dietary essential nutrient. A high intake of polyunsaturated fat requires a concomitant increase in vitamin E in the diet. However, levels above those needed to ensure adequate intake are of questionable benefit. A study showed an increase in several immune function criteria in dogs given supraphysiological levels of vitamin E in the diet (Meydani et al., 1998). However, the amount in the control diet was below that considered adequate for normal nutritive needs according to the Association of American Feed Control Officials (AAFCO)

Dog Food Nutrient Profiles, and there were no intermediate levels of intake tested. Thus, the lowest point at which this beneficial effect is observed could not be determined. A study in cats showed that vitamin E had a mild preventive effect on Heinz body formation and other criteria of oxidative damage due to consumption of propylene glycol and onion powder (Hill et al., 2001).

Vitamin C

Vitamin C functions as an antioxidant inside and outside the cell. It also interacts with vitamin E to help restore the latter's function. It can be synthesized in the body of both dogs and cats and hence is not considered a dietary essential nutrient. Classical signs of deficiency, such as those observed in humans and guinea pigs, have not been documented in these species. Regardless, it is suggested that dietary supplementation may be beneficial, particularly in times of "stress." Studies have shown a slight depression in serum vitamin C concentration in response to some conditions and diseases, and supplementation can increase serum levels in healthy animals (Kronfeld and Donoghue, 1988; Skinner et al., 1999). Vitamin C can also mildly prevent oxidative damage from consumption of propylene glycol or onion powder (Hill et al., 2001). However, definitive evidence of benefit in dogs and cats is lacking. Still, work in other species has shown beneficial effects on immune function, even in species that are able to endogenously synthesize the compound (Machlin, 1993).

Mineral-Dependent Antioxidants

Many trace minerals exhibit at least one of their functions in the body by incorporation into antioxidant enzymes. These include selenium (glutathione peroxidase); copper, zinc, and manganese (superoxide dismutases); and iron (catalase). These enzymes can all be synthesized in sufficient quantities in the body, provided ample amounts of the mineral are available. Studies to demonstrate a benefit of direct inclusion of the enzymes in the diet have not been reported.

Other antioxidants, such as ceruloplasmin and ferritin, are nonenzymatic antioxidants containing copper and iron, respectively. Again, if ample quantities of these minerals are present in the diet, direct supplementation of these compounds is not required.

β-Carotene and Other Carotenoids

β-Carotene and related substances such as lutein and lycopene are derived from plants and are not endogenously synthesized by either dogs or cats. β-Carotene can serve as a precursor to vitamin A in the dog but not the cat. Apart from this function, carotenoids also have antioxidant properties (Machlin, 1993). β-Carotene can be taken up by blood plasma and leukocytes after oral administration in both dogs and cats, and has been shown to stimulate immune response in dogs (Chew et al., 2000b,c,d). However, it is known that β-carotene may exhibit pro-oxidant properties at high levels of intake in humans and laboratory animals (Alpha-Tocopherol, Beta-Carotene Cancer Prevention Study Group, 1994).

One known function of lutein is to help retard age-related degeneration of the macula lutea in the retina of humans (Seddon et al., 1994). However, that specific attribute may be of little service in dogs and cats, since the presence of this structure in the eyes of these species has not been reported (Miller et al., 1964).

Other

A host of other antioxidants have been reported for use in dogs or cats. *S*-Adenosylmethionine (SAMe) is a precursor of glutathione and is used in support of liver function (Center et al., 1999; Davidson, 2002). In a case study, SAMe was also reported to be used in the successful treatment of acetaminophen toxicity in a dog (Wallace et al., 2002). Coenzyme Q_{10} (ubiquinone) is an antioxidant with reported beneficial effects on cardiac function and oral hygiene in dogs (Shizukuishi et al., 1984; Harker-Murray et al., 2000). Long-term administration of α-lipoic acid over 6 months resulted in an increase in the ratio of reduced vs. oxidized glutathione ratios in dogs (Zicker et al., 2002). However, the response was not dose-dependent, and the lowest-supplemented group showed the most significant increase. Because of reduced capacity of cats to metabolize α-lipoic acid compared to dogs, caution is urged for its use in that species (Hill et al., 2002).

Since cats appear prone to oxidative injury, several studies have looked at potential protective effects of antioxidants. A supplement containing bioflavonoids offered before administration of acetaminophen provided some protection against Heinz body formation in red blood cells but did not prevent methemoglobinemia (Allison et al., 2000). Pre-exposure administration of *N*-acetylcysteine, vitamin E, or ascorbate did not appear to significantly affect Heinz body formation in cats challenged with onion powder, although *N*-acetylcysteine administration did result in higher reduced glutathione concentrations in whole blood (Hill et al., 2001). In a second trial of the same antioxidants using propylene glycol as the challenging agent, cats in the antioxidant treatment groups drank less of the water that contained propylene glycol, which may have confounded the results. When the water intake of the control group was normalized to that of the treatment groups, the only antioxidant to show significant effect on Heinz body formation was *N*-acetylcysteine.

Use in Petfoods

The beneficial effects of antioxidant "cocktails" in dog and cat foods have been reported. A combination of supple-

mental vitamin E, vitamin C, and β-carotene increased serum vitamin E concentrations and suppressed serum total alkenyls (biomarkers of lipid peroxidation) in both dogs and cats (Jewell et al., 2000). Supplementation of the diets of Alaskan sled dogs with β-carotene, lutein, and vitamin E "normalized" the adverse effect of exercise on immune status (Chew et al., 2000a). Another cocktail including vitamin E, vitamin C, α-lipoic acid, L-carnitine, and fruit- and vegetable-based ingredients containing flavonoids and carotenoids in a petfood is reported to improve learning ability in older dogs (Milgram et al., 2002). Supplementation with antioxidants improved the length of response to vaccination in adult and senior dogs, although the composition and quantities of the antioxidants in the cocktail were not disclosed (Devlin et al., 2001).

Knowledge of the beneficial effects of antioxidants in the diets of dogs and cats is likely to increase with continued study. Unfortunately, most direct evidence of benefit of antioxidant administration to dogs and cats is from the use of cocktails, so the relative contribution of any single antioxidant is difficult to assess. At this time, there is a lack of data on which to base specific recommendations beyond those for the essential vitamins and minerals that are components of antioxidants.

Probiotics (Direct-Fed Microbials) and Enzymes

Probiotics, or direct-fed microbials, are colonies of live microorganisms often found in the gastrointestinal tract of healthy animals, such as *Lactobacillus*, *Bifidobacterium*, and *Aspergillus*. When added to the diet, they are intended to influence the gut flora by preferentially populating it with nonpathogenic organisms to the exclusion of *Salmonella*, *Escherichia coli*, and other potential pathogens (Biourge et al., 1998). These microorganisms also synthesize vitamins, enzymes, and volatile fatty acids, which may have a beneficial effect on gastrointestinal (GI) health and function, as well as provide and aid in the absorption of nutrients. However, a study using *Bacillus* in dogs failed to show a significant effect on dry matter, protein, fat, or metabolizable energy digestibility (Biourge et al., 1998). The beneficial effects of *Lactobacillus acidophilus* on fecal quality and production of ammonia and putrefactive compounds in dogs was more readily observed when administered in combination with the "prebiotic" fructooligosaccharides (Swanson et al., 2002). The addition of viable *Enterococcus faecium* to the diets of young dogs has been shown to positively affect immune function parameters (Benyacoub et al., 2003).

A microbiologic evaluation of commercial probiotic products intended for animal use (including dogs and cats) revealed that the concentration of live organisms in most products was lower than claimed or even absent (Weese, 2002). Further, some products contained additional species that were not claimed but either had no known probiotic effect or were potentially pathogenic.

Enzymes added to petfoods may be derived from plant sources (e.g., papain from papaya) but are obtained mainly by fermentation of organisms also used as probiotics. The enzyme phytase has been shown to be of benefit in increasing the availability of phosphorus in livestock feed (Lobo, 2000). This can allow for decreases in the amount of phosphorus added to the ration and subsequently decrease its excretion into the environment. Although environmental impact is a key consideration in livestock operations, it is of less concern in the feeding of pets at this time. Other enzymes include proteases, lipases, and amylases, which hypothetically can improve digestion of nutrients by dogs and cats. Increases in absorption of fatty acids, trace minerals, and vitamins were observed with administration of a commercial enzyme product (Ackerman, 1993). However, whether these effects have any practical benefit in animals offered diets that already provide ample quantities of these nutrients is unclear.

Both probiotics and enzymes are at a disadvantage compared to prebiotics (which provide substrates to encourage beneficial gut populations) in that the former are much more sensitive to loss in processing and storage. Microorganisms must remain alive, and enzymes must be active, for them to function as intended. Effects may also be very short-lived, with any benefit quickly negated by cessation of administration. While these technical limitations do not preclude the use of probiotics or enzymes in petfood applications, attention should be paid to the feasibility of inclusion for the potential benefits gained.

Herbs and Botanicals

In whole form, herbs and other botanicals provide some nutritive value in the form of fiber, sugar, oils, and some vitamins and minerals. However, at typical levels, they are unlikely to contribute significantly to the overall nutrient intake of the animal. Rather, their intended use in petfoods is either to provide flavor or, more often, to have an effect on the body other than by nutritional means. This is especially true in the case of extracts, where the classical nutritive components of the plant may be separated from the extract in the process. Since the intended functions are more pharmacologic than nutritional in nature, discussion of potential benefit is beyond the scope of this report.

However, this does not negate potential concerns about the safety of some herbs and botanicals that may be incorporated in petfoods. Adverse effect from ingestion of a substance intended for use by humans containing guarana and ma huang (both contain stimulants to induce appetite suppression) in dogs has been reported (Ooms et al., 2001). However, offending agents are not necessarily limited to the relatively obscure. Garlic and onion, for example, are generally recognized as safe when used as flavoring agents. However, they also are known to cause oxidative damage when consumed in greater quantities (Gfeller and Messonnier, 1998). In fact, onion powder has been used to intentionally

provoke Heinz body formation in cats in some studies (Hill et al., 2001). Although garlic is purported to be beneficial in the treatment and prevention of flea and gastrointestinal parasite infestations, there is little evidence to support its use for these purposes. Inclusion in petfood is imprudent at best.

Another example is St. John's wort. Admittedly not often used in dog or cat foods, it is most often employed to promote "well-being" in human dietary supplement products. However, varieties of this plant are also well known to farmers as a toxic weed (Hulbert and Oehme, 1977). Its bitter taste limits voluntary consumption by livestock, and, when ingested, it can cause photosensitive reactions to UV light, including blistering, edema, and skin necrosis. As a precaution, exposure of pets to sunlight should be limited while the herb is being administered.

Other

L-Carnitine helps to mobilize and metabolize fatty acids in the mitochondria of cells. It is synthesized in the body of dogs and cats, and hence is not considered an essential dietary nutrient. Clinical investigations in American cocker spaniels, Doberman pinschers, and boxers suggest that lack of adequate production by individuals of some breeds of dogs may lead to dilated cardiomyopathy similar to that seen in taurine deficiency in cats (Kittleson, 2000). In other clinical situations, supplementation has been reported to be useful in management of weight loss by beneficially encouraging utilization of body energy and to potentially mitigate the risk of hepatic lipidosis in obese cats on a weight loss regimen (Blanchard, 1997; Center and Sunvold, 2000).

Yucca schidigera extract has no value as a provider of nutritive substances. However, studies have shown it to have some value in reducing offensive fecal odors (Lowe and Kershaw, 1997; Giffard et al., 2001).

CONSTITUENTS INTENDED FOR TECHNICAL OR NONNUTRITIVE EFFECTS ON FOOD

Introduction

A food must do more than provide nutrients. It must also appeal to the senses of taste, smell, sight, and feel if it is to be consumed in quantities needed to provide adequate amounts of essential nutrients. Thus, many constituents of a food are added to affect form, flavor, and other aspects of the food beyond provision of nutrients. Other agents are used to retard degradation of nutrients or formation of compounds that could adversely affect acceptance, or to facilitate the manufacturing process itself.

Many compounds added to dog and cat foods for their technical functions are generally recognized as safe (GRAS) in Title 21 of the Code of Federal Regulations. For these substances there is ample public knowledge of safety, through either published scientific studies or, more often, a long history of safe use in foods and feeds. Status of a substance as GRAS does not imply that it is nontoxic. For example, vitamin D is GRAS; yet, it can induce severe toxic manifestations if fed to excess. A provision of its GRAS status (and that of all substances codified as GRAS) is that it is used in accordance with good manufacturing or feeding practice.

A substance that is not GRAS may still be approved for use in dog or cat foods as a food additive if adequate data are submitted to demonstrate safety and utility. Direct food additives include any of the compounds intended to become a component of the food to achieve its technical effect. Indirect food additives include substances that may become a component of the food through contact with processing machinery and packaging materials, such as lubricants, plastics, and paper components. For purposes of regulation, treatment of a food with ionizing radiation is considered a direct food additive.

Preservatives

Ethoxyquin

Ethoxyquin is a synthetic antioxidant preservative approved for use in animal feeds more than 40 years ago (21 CFR 573.380). It functions to retard degradation of fatty acids and fat-soluble vitamins and formation of peroxide compounds. This is especially important in preserving the quality and acceptability of ingredients containing large quantities of polyunsaturated fats such as fish meal and vitamin premixes.

Although approved for use in all animal feeds, its safety in dog foods has been questioned since the late 1980s (Dzanis, 1991). Questions began when a breeder reported a connection between use of foods containing ethoxyquin and a high incidence of liver cancer in her dogs. Within a few years, similar reports were received, associating use with a wide variety of maladies, including cancer, immune disorders, major organ failures, allergies, reproductive failures, and skin diseases. A review of the published scientific literature could not find data from controlled studies to confirm these purported effects (Dzanis, 1991). Ethoxyquin was found to cause reversible hepatic changes at high doses and to promote certain cancers induced by other chemical substances in laboratory animals (Parke et al., 1973; Fukushima et al., 1984, 1987). One study reported preneoplastic changes in the kidneys of rats receiving high doses of ethoxyquin, but that finding was subsequently refuted (Manson et al., 1987; Hard and Neal, 1990). Contrary to reports of adverse effect, ethoxyquin has also been demonstrated to inhibit other chemically induced neoplasias and have other positive effects (Tsuda et al., 1984; Masui et al., 1986; Manson et al., 1987).

Studies conducted in dogs since then have not uncovered evidence of adverse effect, with one exception. In lactating

bitches receiving doses in food approaching the maximum allowable level of 150 parts per million (ppm), extracellular deposition of protoporphyrin IX in the liver, along with slight increases in serum liver enzymes, was observed. The pigment was a normal intermediate in the synthesis of heme and not chemically related to ethoxyquin. These effects appeared to be mild and wholly reversible upon removal of ethoxyquin from the diet, and no clinical manifestations of these effects were seen. Regardless, to ensure safe use of the preservative in foods intended for all life stages, including gestation-lactation, manufacturers were asked to voluntarily reduce maximum levels of ethoxyquin in dog food from 150 ppm to 75 ppm (FDA, 1997).

Most foods already contained ethoxyquin at or below this reduced level when the request was made. In fact, some manufacturers had removed the ingredient from dog food formulations in response to consumer concerns, despite the lack of scientific evidence of harm. A remaining question is whether ethoxyquin is effective in retarding oxidative damage at these lower levels in the finished food. It can still be used at higher levels in ingredients and premixes to prevent degradation prior to incorporation into the formulation.

No studies on the effect of ethoxyquin in cats are reported in the literature. Although the voluntary reduction in maximum levels requested by FDA does not apply to cat foods, many manufacturers have removed or reduced its use in these products as well.

Propylene Glycol

Propylene glycol is a humectant and antimicrobial preservative, although it has many other functions in foods as well. It is codified as a GRAS general-purpose food additive for use in animal feed (21 CFR 582.1666). Its main purpose in petfoods is to allow them to retain larger percentages of water than would be possible in a dry dog or cat food without resulting in microbial growth and spoilage. Therefore, it is especially useful in the formulation of semimoist foods. It also provides calories and taste to the product. Propylene glycol is often used therapeutically as a source of energy in ruminants suffering from ketosis.

In semimoist foods, propylene glycol is typically used at levels between 6 and 12 percent of the formulation. These dietary levels were known to cause Heinz body formation in the erythrocytes of cats, but observations could not be associated with anemia or other adverse clinical manifestations (Quast et al., 1979). Later studies confirmed that propylene glycol did cause oxidative damage at these levels in cats, which included a decrease in red blood cell half-life, increased susceptibility to damage from other oxidants and disease processes, and changes in the liver and other organs (Christopher, 1989; Christopher et al., 1989; Hickman et al., 1990; Weiss et al., 1990; Bauer et al., 1991, 1992). The level at which these adverse effects were no longer observed was well below amounts needed for the compound to function as a humectant in semimoist foods. Thus, propylene glycol was subsequently prohibited from use in the manufacture of cat foods, with specific note in the federal regulations that it is not GRAS for that intended use (Dzanis, 1994). An informal exception that is not codified is made for its use as a carrier in fat-soluble vitamin premixes, where the resultant level of propylene glycol in the final food is well below the known no observed adverse-effect level. Other compounds, such as glycerin and some organic acids, have been used to mimic the function of propylene glycol in these types of products. Although no work has been reported to show similar effects in dogs at these levels, some manufacturers have substituted these other compounds for propylene glycol in dog formulations as well.

Other

Other synthetic antioxidant preservatives include butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), and tertiary butylhydroquinone (TBHQ). Questions have been raised regarding potential carcinogenic effects of BHA and BHT in human foods (Fukushima et al., 1987). However, currently both are considered GRAS for use in human foods and animal feeds, with the restriction that the total antioxidant content cannot exceed 200 ppm of the fat content of the food or feed (21 CFR 182.3169, 182.3173, 582.3169, and 582.3173). The same restriction applies to the use of the approved food additive TBHQ (21 CFR 172.185). Although not formally approved for use in animal feeds, it is listed as an acceptable feed ingredient by AAFCO as the result of an informal review by FDA (AAFCO, 2003).

Mixed tocopherols include forms of vitamin E that have antioxidant preservative functions similar to ethoxyquin and other synthetic preservatives (21 CFR 582.3890). Because they are extracted from plant materials without further chemically synthetic processes, tocopherols are often marketed as "natural" preservatives. However, the amounts needed to achieve this function may be higher and may not last as long as the synthetic alternatives (Gross et al., 1994). Compounds with the highest functionality with respect to preservation of food include the γ- and δ-tocopherols, as opposed to the form with the highest nutritional value (α-tocopherol). Also, unlike the nutritional form of vitamin E, mixed tocopherols cannot be altered synthetically to include a moiety that helps prevent oxidative degradation in vitro (e.g., acetate, succinate). Addition of this moiety is prudent for nutritional sources of the vitamin, since it helps prevent degradation in the food prior to consumption. However, the same chemical modification would also prevent vitamin E from functioning as a preservative while in the food. In performing its function, mixed tocopherols are destroyed. Other agents, such as ascorbic or citric acids or rosemary extract, are sometimes used to help recycle the function of the tocopherol compounds. Rosemary extract is not approved for use as a preservative, however.

Benzoic acid is an antifungal chemical preservative that is classified as GRAS for use in animal feeds at levels not to exceed 0.1 percent of the formulation (21 CFR 582.3021). Cats appear particularly sensitive to adverse effects because of reduced ability to metabolize this compound. The maximal tolerated dose in cats is reported to be 200 mg·kg $BW^{-1}·d^{-1}$ when given for 15 days (Bedford and Clarke, 1972). At allowed use levels an adequate margin of safety should still exist. For example, a 4-kg adult cat consuming 80 g a day of a food containing 0.1 percent benzoic acid would consume 20 mg·kg $BW^{-1}·d^{-1}$.

Sodium and potassium salts of bisulfite and metabisulfite are preservatives most often used in wine production to sanitize equipment and stop the growth of yeast. Complaints of adverse reactions to consumption of sulfites prompted the requirement for label disclosure on commercial wine. Sulfites are GRAS for use in animal feed, with two exceptions (21 CFR 582.3616, 582.3637, 582.3739, and 582.3776). Use of sulfites on meat may misleadingly conceal a lack of freshness; so, they are prohibited from this use under the regulation. Also, because of the potential for sulfites to destroy thiamin, regulations do not consider them GRAS for use in products intended to serve as a source of thiamin for animals. Thiamin deficiency has been demonstrated in dogs and cats in Australia that were fed a fresh meat product containing sulfur dioxide (Studdert and Labue, 1991). Because of their potential adverse effect on thiamin, use of sulfites would be precluded in dog and cat products intended to serve as the sole source of nutrition in the United States.

Sodium and potassium salts of nitrite and nitrate are prior sanctioned by the U.S. Department of Agriculture for use in cured meat and poultry products for human consumption as a preservative and color fixative (21 CFR 181.33 and 181.34). When the sodium salts are used to cure smoked fish or sold as a retail product for home-curing meat and meat products for human consumption, the final product cannot contain more than 500 ppm sodium nitrate and 200 ppm sodium nitrite (21 CFR 172.170 and 172.175). Concern has been expressed about the use of these substances in human foods, particularly about the formation of potentially carcinogenic nitrosamines during high-temperature cooking. Regardless, because of the nature of most petfood products, use of these substances is limited. The only approval for use of sodium nitrite in animal feed is in canned petfood containing meat or fish, and there it is limited to 20 ppm (21 CFR 573.700). There are no regulations sanctioning the use of sodium nitrate or potassium salts of either compound in animal feed.

Flavors and Extracts

Digests

Digests are the results of chemical or enzymatic hydrolysis of animal tissues, including those derived from meat, poultry, or fish. As such, they are considered "natural" flavors as the term is used in the pertinent regulations (21 CFR 501.22(a)(3)). Digests are used to increase palatability by replacing or accentuating the predominant flavor of food. Only small quantities of digests are needed to achieve their intended effects as flavors. However, even in amounts used, many digests contain concentrations of phosphoric acid that are sufficient to influence total phosphate intake. Phosphoric and other acids in digests may also be present in amounts capable of influencing urine pH when consumed.

Other Natural Flavors

A wide variety of flavors can be derived from other animal and plant materials including dairy products, eggs, herbs, and spices. Acceptable processing methods include roasting, extraction, and fermentation.

Many herbs and similar flavoring agents that are acceptable for use in animal feeds and petfoods are sometimes added for other intended effects, such as an antiparasitic agents (garlic), antioxidants (rosemary), or agents having effects other than taste (parsley, turmeric, licorice, chamomile). These alternative functions are not recognized as legitimate intended uses under federal regulations, and claims alluding to function beyond provision of flavor may prompt regulatory action. There are few data to suggest that these substances would be of benefit at levels typically added as flavors.

Artificial Flavors

A host of various synthetic compounds available simulate vanilla, fruits, and many other flavors. Artificial flavors allowed for use in human food products may also be used in animal feeds. Except for artificial smoke and bacon flavors, synthetic substances are rarely used in most dog and cat foods, and then mainly in treat products.

Colors

Certified

Certified colors are synthetic compounds used to replace or accentuate the inherent color of food (21 CFR 74.101 through 74.706). In addition to the need for the substance to undergo an approval process prior to marketing, each batch must be individually certified to ensure safe use. These substances are identified on the label by the color and a designated number, such as "Red 40" and "Blue 1." Although the use of a color additive in a petfood would have an arguable effect on the acceptability of the product to a dog or cat, it can influence pet owner purchase and use. Only certified colors approved for use in human foods are allowed in petfoods. One potential drawback of inclusion of either certified or noncertified colors is a change in color of the feces.

While this is not considered detrimental to the animal, a permanent stain may be left if the feces has contact with some household surfaces.

Non-certified

Color additives that are approved but are exempt from certification procedures can be synthetically derived (e.g., iron oxide, titanium dioxide), but more often are obtained from natural sources such as spices (paprika, saffron), fruits and vegetables, caramel, and other sources (carmine from the insect *Dactyloptus coccus*) (21 CFR 73.1 through 73.1991). Irrespective of their sources, none can be identified as "natural" color, since any substance added to a food intended only to alter its inherent color is "artificial" (21 CFR 501.22(a)(4)). For example, beets added to a product would change the color of the final food but would also add nutrients and flavor. On the other hand, beet juice (21 CFR 73.260) would not provide these additional attributes; hence the resultant color would not be considered natural. Also, approval of a substance as a color does not imply approval as a source of nutrients or other functional benefit (e.g., marigold extract as a source of lutein) (21 CFR 73.295).

Iron Oxide and Titanium Dioxide

Iron oxide is a synthetic but noncertified color used to give dog and cat food a red, meaty appearance (21 CFR 73.200). It can be used at levels not to exceed 0.25 percent of the product. At these levels, it can influence the total iron concentration in the formula. However, iron oxide is very poorly bioavailable to dogs and cats (Chausow and Czarnecki-Maulden, 1987). Thus, it cannot be used as a nutritional source of iron in commercial dog and cat foods, nor can its contribution to the total iron content be considered in determination of whether a petfood meets the AAFCO Dog or Cat Food Nutrient Profiles (AAFCO, 2003).

Titanium dioxide is another common color additive in human food and petfoods. Because it can impart a brilliant white color alone, a more common use is in cosmetics, but it can also induce a "brightness" in foods by complementing other color additives. Its use is limited to 1 percent of the food by weight (21 CFR 73.575).

Other Additives

Many other additives are approved for use to facilitate the manufacturing process or affect the stability, form, and other technical qualities of the food. These include anticaking agents (primarily silica salts), dust control agents, and die lubricants such as mineral oil, emulsifiers, gums and other stabilizers, and sequestrants. Sequestrants such as sodium hexametaphosphate have also been added to foods for the purpose of controlling dental calculus formation (Stookey et al., 1995, 1996). These function by sequestering minerals to form soluble complexes, thus preventing mineralization of dental plaque to form calculi. However, although this and related compounds are GRAS as technical food additives, the use of sequestrants for the purpose of affecting dental calculus formation has not been approved to date.

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15

Nutrient Requirements and Dietary Nutrient Concentrations

The purpose of this chapter is to assemble and present the nutrient data discussed in this report in an easy-to-use summary. In Tables 15-2 through 15-14, nutrient data are presented for energy, protein and amino acids, fat and fatty acids, macro- and microminerals, and vitamins. Because it is known that the requirements for nutrients vary with differing physiological states of an animal, separate tables of the nutrient data are provided for cats and dogs during growth, for adult maintenance, and during gestation and lactation.

Normal animal health and physiology can only be maintained if the intake of all nutrients meets the minimal requirements on a continuing basis. Minimal requirement data are derived from peer-reviewed literature, and, although research on the nutrient requirements of dogs and cats has appeared since the last publications on dog and cat nutrition (NRC, 1985, 1986), large gaps in our knowledge of the quantitative requirements for specific nutrients still exist. These gaps are noted in the text and by the absence of data in the requirement tables.

The nutrient requirement data for dogs and cats are provided in four distinct categories, presented in tabular form. First, the *Minimal Requirement* (MR) is given; this term is defined as the minimal concentration or amount of a bioavailable nutrient that will support a defined physiological state.

The next column presents *Adequate Intake* (AI), which is defined as the concentration in the diet or amount required by the animal of a nutrient that is presumed to sustain a given life stage when no MR has been demonstrated. The AI is based on published data demonstrating the adequacy of a concentration or amount of nutrient for a given life stage in the target species, which is supported, in some cases, by comparative data from studies in other species.

Next, the *Recommended Allowance* (RA) for each nutrient is presented. The RA is defined as the concentration or amount of a nutrient in a diet formulated to support a given physiological state. The RA is based on the MR and, where applicable, includes a safety factor for nutrients with uncertain bioavailability. If no MR is available, the RA is based on the AI.

Finally, values for the *Safe Upper Limit* (SUL) are presented. The SUL values are based on the maximal concentration or amount of a nutrient that has not been associated with adverse effects in dogs and cats. Unfortunately, SUL values are not available for many required nutrients, especially minerals and vitamins.

To meet the desired amount of nutrient intake, the diet consumed must contain the proper concentration of each nutrient. Because animals normally eat to satisfy their energy requirement, one way to express the dietary nutrient concentrations is as unit(s) or nutrient per 1,000 kilocalories (kcal) of metabolizable energy. It is also possible to express the dietary concentrations as unit(s) per kilogram (kg) of diet. The tables provide this information both ways, but to standardize the tabulated data for all nutrients, the following assumptions were made:

The energy density of the diet for both dogs and cats was assumed to be 4,000 kcal of metabolizable energy (ME) per kg. Requirements for growth in puppies are based on a 5.5-kg puppy that consumes 1,000 kcal of ME per day. Requirements for adult dogs at maintenance are based on a 15-kg adult dog that consumes 1,000 kcal ME per day. Requirements for gestating and lactating bitches are based on a 22-kg bitch with eight puppies in peak lactation consuming 5,000 kcal of ME per day. Requirements for growth of kittens are based on an 800-g kitten consuming 180 kcal of ME per day, and those for adult cats at maintenance are based on a 4-kg adult cat consuming 250 kcal of ME per day. Requirements for gestating and lactating cats are based on a 4-kg queen with four kittens in peak lactation consuming 540 kcal of ME per day.

With the exception of amino acid requirements in gestating queens, there is a lack of experimental data for nutrient requirements of gestating cats and dogs. In general, however, the nutrient requirements of lactating animals are likely to be sufficient for gestation. The values provided in

the tables for lactating cats and dogs can be used for gestating animals after adjusting for differences in caloric intake. Information on how to correct for the difference is included in the footnotes to the tables.

In addition to providing data on dietary nutrient concentrations as (1) amount of nutrient per kg of dietary dry matter (DM) (which is assumed to contain 4,000 kcal ME) and (2) amount of nutrient per 1,000 kcal of ME, the tables also provided the data expressed as (3) amount of nutrient per kg of metabolic body weight, that is, body weight to the 0.75 exponent ($BW^{0.75}$) per day for dogs and body weight to the 0.67 exponent ($BW^{0.67}$) per day for cats. The pros and cons of developing diets based on any particular expression of nutrient requirements are discussed later in this chapter.

Energy requirements are expressed as kcal of ME per kg of $BW^{0.75}$ per day for dogs at maintenance and for pregnant bitches. For lactating bitches, energy requirements are a function of both $BW^{0.75}$ and body weight (BW) as well as number of suckling puppies. Daily energy requirements for growing dogs are based on maintenance requirements multiplied by a factor that is a function of the ratio between actual BW and expected mature BW. The equations for energy requirements in dogs are based on data of dogs between 4 and 60 kg of mature weight, except for female reproduction where the majority of data were obtained from dogs between 5 and 25 kg BW.

The equations for energy requirements in cats are based on data of domestic cats between 2.5 and 7 kg of mature weight. Energy requirements for cats at maintenance are expressed as kcal of ME per kg $BW^{0.67}$ per day for cats with body condition scores equal to or less than 5.0 (on a 9-point scale) and as per kg $BW^{0.4}$ for cats with body condition scores greater than 5.0. For pregnant queens, energy requirements are expressed as a function of $BW^{0.67}$, whereas, for lactating queens, energy requirements are a function of both $BW^{0.67}$ and BW as well as number of suckling kittens. Daily energy requirements for growing cats are based on maintenance requirements multiplied by a factor that is a function of the ratio between actual BW and expected mature BW.

USE OF NUTRIENT REQUIREMENT TABLES

Expressing a requirement relative to DM or ME is most convenient when formulating a diet for general use in feeding dogs and cats, such as in commercial diets, but expressing a requirement relative to metabolic BW may be more convenient when formulating a diet for an individual. Unfortunately, requirements expressed relative to DM change with the energy density of the diet. In a few instances, there is also a suggestion that requirements expressed relative to ME may change with BW. These issues are discussed in the following paragraphs, and information as to how to correct for dogs and cats of differing sizes has been included as footnotes to the tables.

Recommendations Relative to ME Compared with Requirements Relative to DM

Nutrient recommendations for dogs and cats are best expressed relative to ME rather than relative to DM because ME, not DM, determines the amount of food that must be consumed by a dog or cat to maintain BW and body condition score. Requirements expressed relative to ME do not change as the energy density of a diet changes, whereas requirements relative to DM vary with energy density of the food. For some nutrients, requirements have been established experimentally relative to DM rather than ME. These have been converted to requirements expressed relative to ME, at an energy density of 4,000 kcal ME·kg^{-1} DM. Following this conversion, it is the requirements and allowances expressed relative to ME, not those expressed relative to DM, that remain constant as the energy density of the diet changes.

For example, a cat maintaining its BW while consuming 240 kcal ME would have to eat 60 g DM of a food that contains 4,000 kcal ME·kg^{-1} DM but would have to consume 80 g of a food containing only 3,000 kcal ME·kg^{-1} DM. In this example, a nutrient that must be included at a minimum of 8 g·kg^{-1} DM in the first diet need only be included at a concentration of 6 g·kg^{-1} DM in the second, but the nutrient requirement relative to ME remains the same (2 g per 1,000 kcal ME in this example) in both diets.

Thus, when using the tables to determine how much nutrient should be included in the diet when the nutrient density of a diet is not 4,000 kcal ME·kg^{-1}, the value of the requirement relative to kg DM reported in the table should be multiplied by the energy density of the new diet (in kilocalories ME per kg) and divided by 4,000.

Requirements Relative to ME in the Food Compared with Requirements Relative to BW

There is little information about how nutrient requirements vary with BW. Many nutrient requirements vary, as do maintenance energy requirements, relative to metabolic BW (BW with an exponent of 0.75 in lean dogs and 0.67 in lean cats; Rucker and Steinberg, 2002; Rucker and Storms, 2002). Other requirements may vary directly with BW or with some other exponent (Rivers and Burger, 1989).

Several authors, for example, have suggested that endogenous nitrogen output and, by inference, protein requirements vary with an exponent of approximately 0.75 (Miller and Payne, 1963; Kendall et al., 1982; Rivers and Burger, 1989). In dogs, Kendall et al. (1982) reported the endogenous nitrogen output to be 273 mg·kg $BW^{-0.75}$, which suggests an MR of 1.7 g crude protein·kg $BW^{-0.75}$. Protein requirements expressed relative to ME in the diet should remain, therefore, almost constant irrespective of BW and are best expressed relative to ME (Schaeffer et al., 1989). The requirements for some minerals may vary more directly

with BW, however, and, for these nutrients, requirements relative to ME will vary with BW. Variation with BW may need to be considered when making diets for individuals using MRs and SULs. Recommendations for maintenance in the tables have been calculated by assuming a moderate-sized lean adult dog of 15 kg BW and a moderate-sized lean adult cat of 4 kg BW. For nutrients whose requirements are thought to vary with metabolic BW, recommendations expressed relative to ME will remain the same, irrespective of body size. For nutrients whose requirements are thought to vary directly with BW, requirements expressed relative to ME will increase or decrease with BW, with an exponent of 0.25 for lean dogs and 0.33 for lean cats, as shown in Table 15-1. In this case, the requirement relative to ME will be about 40 percent greater in a 6-kg cat than in a 2-kg cat and twice as large for a 100-kg dog as for a 2-kg dog (i.e., the diet would need to be more nutrient dense for a large than for a small animal).

TABLE 15-1 Change in Requirements Relative to ME (per 1,000 kcal) if Requirements Vary Directly with BW

Species	BW (kg)	Change (%)
Dog	2	– 40
	5	– 24
	10	– 10
	15	No change
	20	+ 7
	40	+ 28
	60	+ 41
	80	+ 52
	100	+ 61
Lean cat	2	– 20
	3	– 9
	4	No change
	5	+ 8
	6	+ 14

Table 15-1 is intended to illustrate the concept that, for nutrients whose requirements vary directly with BW, the value of those nutrient requirements expressed relative to ME will increase or decrease with differences in BW. The table should not be used to formulate diets. Rather, the reader is directed to the footnotes in each of the subsequent tables in Chapter 15 that provide information on how to calculate requirements for cats and dogs of different sizes.

Note on Bioavailability

The proposed minimal concentrations and amounts of vitamins are the total bioavailable forms of the vitamins present in the diet (contributed by natural ingredients and vitamin premixes) at the point of consumption. Because the natural forms of some vitamins have low bioavailabilities, the proposed amount will generally be adequate when the majority of that vitamin is from a vitamin premix. However, when a vitamin is contributed mainly by food ingredients, the minimal concentration in the tables should be modified to account for bioavailability by using a suitable factor. For a discussion of the bioavailability of vitamins from various foods, refer to Baker (1995).

The reader should take note that this published report reflects a number of changes made to correct and update an unedited prepublication version of this report. Some values, particularly in Chapter 15, have been revised or deleted based on the availability of new information or to correct errors in calculation. These changes were examined by four independent reviewers and have been approved by the authoring committee and the institution. This final published version of the report therefore supersedes the data contained in the prepublication.

TABLE 15-2 Daily Metabolizable Energy Requirements for Growth of Puppies After Weaning[a,b]

$$\text{ME (kcal)} = \text{maintenance amount} \times 3.2 \times [e^{(-0.87p)} - 0.1]$$

$$\text{ME (kcal)} = 130 \times BW_a^{0.75} \times 3.2 \times [e^{(-0.87p)} - 0.1]$$

Where:

$p = BW_a/BW_m$

BW_a = actual body weight at time of evaluation (kg)

BW_m = expected mature body weight (kg)

e = base of natural log ≈ 2.718

Example:

Labrador puppy 16 weeks of age, 17 kg actual body weight, expected mature weight 35 kg

$\text{ME (kcal)} = 130 \times 17^{0.75} \times 3.2 \times [e^{(-0.87 \times 17/35)} - 0.1] = 1{,}934$ kcal

[a]This table refers to puppies after weaning. Newborn puppies need about 25 kcal per 100 g BW (Kienzle et al., 1985).

[b]Maintenance energy requirements of inactive puppies such as pet puppies without opportunity and/or stimulus to exercise may be lower by 10 to 20 percent, and maintenance energy requirements of very active puppies, such as Great Danes in kennels, may be higher.

TABLE 15-3 Nutrient Requirements for Growth of Puppies After Weaning

Nutrient	Minimal Requirement			Adequate Intake			Recommended Allowance			Safe Upper Limit		
	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.75}$[c]	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.75}$[c]	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.75}$[c]	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.75}$[c]
Growing Puppies 4-14 Weeks Old												
Crude Protein (g)	180	45	12.5				225	56.3	15.7			
Amino Acids												
Arginine (g)[d]	6.3	1.58	0.44				7.9	1.98	0.55			
Histidine (g)	3.1	0.78	0.22				3.9	0.98	0.27			
Isoleucine (g)	5.2	1.30	0.36				6.5	1.63	0.45			
Methionine (g)	2.8	0.70	0.19				3.5	0.88	0.24			
Methionine & Cystine (g)	5.6	1.40	0.39				7.0	1.75	0.49			
Leucine (g)	10.3	2.58	0.72				12.9	3.22	0.90			
Lysine (g)	7.0	1.75	0.49				8.8	2.20	0.61	>20	>5.0	>1.39
Phenylalanine (g)	5.2	1.30	0.36				6.5	1.63	0.45			
Phenylalanine & Tyrosine (g)[e]	10.4	2.60	0.72				13.0	3.25	0.90			
Threonine (g)	6.5	1.63	0.45				8.1	2.03	0.56			
Tryptophan (g)	1.8	0.45	0.13				2.3	0.58	0.16			
Valine (g)	5.4	1.35	0.38				6.8	1.70	0.47			
Growing Puppies 14 Weeks and Older												
Crude Protein (g)	140	35	9.7				175	43.8	12.2			
Amino Acids												
Arginine (g)[d]	5.3	1.33	0.37				6.6	1.65	0.46			
Histidine (g)	2.0	0.50	0.14				2.5	0.63	0.17			
Isoleucine (g)	4.0	1.00	0.28				5.0	1.25	0.35			
Methionine (g)	2.1	0.53	0.15				2.6	0.65	0.18			
Methionine & Cystine (g)	4.2	1.05	0.29				5.3	1.33	0.37			
Leucine (g)	6.5	1.63	0.45				8.2	2.05	0.57			
Lysine (g)	5.6	1.40	0.39				7.0	1.75	0.49	>20	>5.0	>1.39
Phenylalanine (g)	4.0	1.00	0.28				5.0	1.25	0.35			
Phenylalanine & Tyrosine (g)[e]	8.0	2.00	0.56				10.0	2.50	0.70			
Threonine (g)	5.0	1.25	0.35				6.3	1.58	0.44			
Tryptophan	1.4	0.35	0.10				1.8	0.45	0.13			
Valine (g)	4.5	1.13	0.31				5.6	1.40	0.39			
Growing Puppies After Weaning												
Total Fat (g)				85	21.3	5.9	85	21.3	5.9	330[a]	82.5	23.0
Fatty Acids												
Linoleic Acid (g)				11.8	3.0	0.8	13	3.3	0.8	65[a]	16.3	4.5
α-Linolenic Acid (g)[f]				0.7	0.18	0.05	0.8	0.2	0.05			
Arachidonic Acid (g)				0.3	0.08	0.022	0.3	0.08	0.022			
Eicosapentaenoic & Docosahexaenoic Acid (g)[g]				0.5	0.13	0.036	0.5	0.13	0.036	11[a]	2.8	0.77
Minerals												
Calcium (g)[h]	8.0	2.0	0.56				12[h]	3.0[h]	0.68[h]	18	4.5	1.25
Phosphorus (g)				10	2.5	0.68	10	2.5	0.68			
Magnesium (mg)	180	45	12.5				400	100	27.4			
Sodium (mg)				2,200	550	100	2,200	550	100			
Potassium (g)				4.4	1.1	0.30	4.4	1.1	0.30			

(continued)

TABLE 15-3 (continued)

Nutrient	Minimal Requirement			Adequate Intake			Recommended Allowance			Safe Upper Limit		
	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.75}$[c]	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.75}$[c]	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.75}$[c]	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.75}$[c]
Chloride (mg)				2,900	720	200	2,900	720	200			
Iron (mg)[i]	72	18	5.0				88	22	6.1			
Copper (mg)[i]				11	2.7	0.76	11	2.7	0.76			
Zinc (mg)	40	10	2.7				100	25	6.84			
Manganese (mg)				5.6	1.4	0.38	5.6	1.4	0.38			
Selenium (µg)	210	52.5	13.7				350	87.5	25.1			
Iodine(µg)				880	220	61.0	880	220	61.0			
Vitamins												
Vitamin A (RE)[j]				1,212	303	84	1,515	379	105	15,000[j]	3,750[j]	1,044[j]
Cholecalciferol (µg)[k]				11.0	2.75	0.76	13.8	3.4	0.96	80	20	5.6
Vitamin E (α-tocopherol) (mg)[l]				24	6.0	1.7	30	7.5	2.1			
Vitamin K (Menadione) (mg)[m]				1.3	0.33	0.090	1.64	0.41	0.11			
Thiamin (mg)				1.08	0.27	0.075	1.38	0.34	0.096			
Riboflavin (mg)				4.2	1.05	0.27	5.25	1.32	0.37			
Pyridoxine (mg)				1.2	0.3	0.084	1.5	0.375	0.10			
Niacin (mg)				13.6	3.4	0.94	17.0	4.25	1.18			
Pantothenic Acid (mg)				12	3.0	0.84	15.0	3.75	1.04			
Cobalamin (µg)				28	7	1.95	35	8.75	2.4			
Folic Acid (µg)				216	54	15.0	270	68	18.8			
Biotin[n]												
Choline (mg)				1,360	340	95	1,700	425	118			

[a]The values for Amt/kg DM have been calculated assuming a dietary energy density of 4,000 kcal ME/kg. (The term ≡ signifies equivalence.) If the energy density of the diet is not 4,000 kcal ME/kg, then to calculate the Amt/kg DM for each nutrient, multiply the value for the nutrient in the column labeled Amt/kg DM by the energy density of the pet food (in kcal ME/kg) and divide by 4,000.

[b]To calculate the amount to feed of each nutrient, multiply the value for Amt/1,000 kcal ME for each nutrient by the energy requirement for the puppy in kcal (calculated from Table 15-2) and divide by 1,000.

[c]The values for Amt/$BW^{0.75}$ apply only to 5.5-kg puppies of expected mature body weight of 35 kg. To calculate the amount of a nutrient for puppies of different current or expected mature body weights, calculate the energy requirement from Table 15-2 and multiply this by the nutrient Amt/1,000 kcal and divide by 1,000.

[d]For 4 to 14 week-old puppies, 0.01 g arginine should be added for every g of crude protein above 180 g and 225 g, for the MR and RA, respectively, of arginine. For puppies over 14 weeks of age, 0.01 g arginine should be added for every g of crude protein above 140 g and 175 g for the MR and RA of arginine, respectively.

[e]The quantity of tyrosine required to maximize black hair color may be about 1.5-2.0 times this quantity.

[f]The requirement for α-linolenic acid varies depending upon linoleic acid content of the diet. The ratio of linoleic acid to α-linolenic acid should be between 2.6 and 16. Note that 0.8 g/kg DM value shown is the minimum RA of α-linolenic acid at 13 g linoleic acid per kg DM, resulting in a ratio of linoleic acid to α-linolenic acid of approximately 16.

[g]Eicosapentaenoic acid should not exceed 60% of the total amount.

[h]The RA for the calcium requirements of weaned puppies (of expected mature body weight >25 kg) for up to 14 weeks of life should not be less than 0.54 g calcium/kg body weight.

[i]Some oxide forms of iron and copper should not be used because of low bioavailability.

[j]For vitamin A, requirements are expressed as RE (retinol equivalents). One RE is equal to 1 µg of all-*trans* retinol, and one IU of vitamin A is equal to 0.3 RE. Safe upper limit values are expressed as µg retinol.

[k]1 µg cholecalciferol = 40 IU vitamin D_3.

[l]Higher concentrations of vitamin E are recommended for high PUFA diets. One international unit of vitamin E = 1 mg all-*rac*-α-tocopheryl acetate (see Chapter 8).

[m]Dogs have a metabolic requirement, but a dietary requirement has not been demonstrated when natural diets are fed. Adequate vitamin K is probably synthesized by intestinal microbes. The vitamin K allowance is expressed in terms of the commercially used precursor menadione that requires alkylation to the active vitamin K.

[n]For normal diets not containing raw egg white, adequate biotin is probably provided by microbial synthesis in the intestine. Diets containing antibiotics may need supplementation.

TABLE 15-4 Daily Metabolizable Energy Requirements for Adult Dogs at Maintenance

Type	Kcal × kg $BW^{0.75}$
Average for laboratory kennel dogs or active pet dogs[a]	130
Above average requirements:	
Young adult laboratory dogs or young adult active pet dogs	140
Adult laboratory Great Danes or active pet Great Danes	200
Adult laboratory terriers or active pet terriers	180
Below average requirements:	
Inactive pet dogs[b]	95
Older laboratory dogs or older active pet dogs or laboratory Newfoundlands	105

[a]Dogs kept in a domestic environment with strong stimulus and ample opportunity to exercise, such as dogs in multiple dog households in the country or in a house with a large yard.
[b]Dogs kept in a domestic environment with little stimulus and opportunity to exercise. Requirements of older or overweight dogs may still be overestimated.

TABLE 15-5 Nutrient Requirements of Adult Dogs for Maintenance

	Minimal Requirement			Adequate Intake			Recommended Allowance			Safe Upper Limit		
Nutrient	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.75}$	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.75}$	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.75}$	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.75}$
Crude Protein (g)	80	20	2.62				100	25	3.28			
Amino Acids												
Arginine (g)[c]	2.8	0.70	0.092				3.5	0.88	0.11			
Histidine (g)	1.5	0.37	0.048				1.9	0.48	0.062			
Isoleucine (g)	3.0	0.75	0.098				3.8	0.95	0.12			
Methionine (g)	2.6	0.65	0.085				3.3	0.83	0.11			
Methionine & Cystine (g)	5.2	1.30	0.17				6.5	1.63	0.21			
Leucine (g)	5.4	1.35	0.18				6.8	1.70	0.22			
Lysine (g)	2.8	0.70	0.092				3.5	0.88	0.11			
Phenylalanine	3.6	0.90	0.12				4.5	1.13	0.15			
Phenylalanine & Tyrosine (g)[d]	5.9	1.48	0.19				7.4	1.85	0.24			
Threonine (g)	3.4	0.85	0.11				4.3	1.08	0.14			
Tryptophan (g)	1.1	0.28	0.036				1.4	0.35	0.046			
Valine (g)	3.9	0.98	0.13				4.9	1.23	0.16			
Total Fat (g)				40	10	1.3	55	13.8	1.8	330[a]	82.5	10.8
Fatty Acids												
Linoleic Acid (g)				9.5	2.4	0.3	11	2.8	0.36	65[a]	16.3	2.1
α-Linolenic Acid(g)[e]				0.36	0.09	0.012	0.44	0.11	0.014			
Arachidonic Acid (g)												
Eicosapentaenoic + Docosahexaenoic Acid (g)[f]				0.44	0.11	0.03	0.44	0.11	0.03	11[a]	2.8	0.37
Minerals												
Calcium (g)	2.0	0.50	0.059				4.0	1.0	0.13			
Phosphorus (g)				3.0	0.75	0.10	3.0	0.75	0.10			
Magnesium (mg)	180	45	5.91				600	150	19.7			

(continued)

TABLE 15-5 (continued)

Nutrient	Minimal Requirement			Adequate Intake			Recommended Allowance			Safe Upper Limit		
	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.75}$	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.75}$	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.75}$	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.75}$
Sodium (mg)	300	75	9.85				800	200	26.2	>15 g		
Potassium (g)				4.0	1.0	0.14	4.0	1.0	0.14			
Chloride (mg)				1,200	300	40	1,200	300	40	23.5 g		
Iron (mg)[g]				30	7.5	1.0	30	7.5	1.0			
Copper (mg)[g]				6	1.5	0.2	6	1.5	0.2			
Zinc (mg)				60	15	2.0	60	15	2.0			
Manganese (mg)				4.8	1.2	0.16	4.8	1.2	0.16			
Selenium (µg)				350	87.5	11.8	350	87.5	11.8			
Iodine (µg)	700	175	23.6				880	220	29.6	≥ 4 mg		
Vitamins												
Vitamin A (RE)[h]				1,212	303	40	1,515	379	50	64,000[h]	16,000[h]	2,099[h]
Cholecalciferol (µg)[i]				11.0	2.75	0.36	13.8	3.4	0.45	80	20	2.6
Vitamin E (α-tocopherol) (mg)[j]				24	6.0	0.8	30	7.5	1.0			
Vitamin K (Menadione) (mg)[k]				1.3	0.33	0.043	1.63	0.41	0.054			
Thiamin (mg)				1.8	0.45	0.059	2.25	0.56	0.074			
Riboflavin (mg)	4.2	1.05	0.138				5.25	1.3	0.171			
Pyridoxine (mg)				1.2	0.30	0.04	1.5	0.375	0.049			
Niacin (mg)				13.6	3.4	0.45	17.0	4.25	0.57			
Pantothenic Acid (mg)				12	3.0	0.39	15	3.75	0.49			
Cobalamin (µg)				28	7	0.92	35	8.75	1.15			
Folic Acid (µg)				216	54	7.1	270	67.5	8.9			
Biotin[l]												
Choline (mg)				1,360	340	45	1,700	425	56			

[a]The values for Amt/kg DM have been calculated assuming a dietary energy density of 4,000 kcal ME/kg. (The term ≡ signifies equivalence.) If the energy density of the diet is not 4,000 kcal ME/kg, then to calculate the Amt/kg DM for each nutrient, multiply the value for the nutrient in the column labeled Amt/kg DM by the energy density of the pet food (in kcal ME/kg) and divide by 4,000.

[b]To calculate the amount to feed of each nutrient, multiply the value for Amt/1,000 kcal ME for each nutrient by the energy requirement for laboratory kennel dogs in kcal (calculated from Table 15-4) and divide by 1,000. For dogs with an unusually low energy intake (below the suggested requirement), the nutrient concentrations (Amt/1,000 kcal) may not be adequate. These animals should be fed the nutrient amounts shown in the column Amt/kg $BW^{0.75}$.

[c]0.01 g arginine should be added for every g of crude protein above 80 g and 100 g for the MR and RA, respectively.

[d]The quantity of tyrosine required to maximize black hair color may be about 1.5-2.0 times this quantity.

[e]The requirement for α-linolenic acid varies depending upon linoleic acid content of the diet. The ratio of linoleic acid to α-linolenic acid should be between 2.6 and 26. Note that 0.44 g/kg DM value shown is the minimum RA of α-linolenic acid at 11 g linoleic acid per kg DM, resulting in a ratio of linoleic acid to α-linolenic acid of approximately 25.

[f]50-60% of the total amount should be eicosapentaenoic acid, and 40-50% should be docosahexaenoic acid.

[g]Some oxides of iron and copper should not be used because of low bioavailability.

[h]Vitamin A requirements expressed as RE (retinol equivalents). One RE is equal to 1 µg of all-*trans* retinol, and one IU of vitamin A is equal to 0.3 RE. Safe upper limit values expressed as µg retinol.

[i]1 µg cholecalciferol = 40 IU vitamin D_3.

[j]Higher concentrations of vitamin E are recommended for high PUFA diets. One international unit of vitamin E = 1 mg all-*rac*-α-tocopheryl acetate (see Chapter 8).

[k]Dogs have a metabolic requirement, but a dietary requirement has not been demonstrated when natural diets are fed. Adequate vitamin K is probably synthesized by intestinal microbes. The vitamin K allowance is expressed in terms of the commercially used precursor menadione that requires alkylation to the active vitamin K.

[l]For normal diets not containing raw egg white, adequate biotin is probably provided by microbial synthesis in the intestine. Diets containing antibiotics may need supplementation.

TABLE 15-6 Daily Metabolizable Energy Requirements for Bitches in Late Gestation (4 Weeks After Mating Until Parturition)[a]

ME (kcal) = maintenance + 26 kcal × kg BW
Average maintenance requirements 130 kcal × kg $BW^{0.75}$
ME (kcal) = 130 kcal × kg $BW^{0.75}$ + 26 kcal × kg BW

Example:
Body weight of bitch 22 kg
Maintenance requirements $22^{0.75} \times 130$ kcal = 10.16 × 130 = 1,320 kcal
Requirements for gestation 22 × 26 kcal = 572 kcal
Total requirements 1,320 kcal + 572 kcal = 1,892 kcal

[a]For variations in maintenance requirements, see Table 15-4.

TABLE 15-7 Daily Metabolizable Energy Requirements for Lactating Bitches Based on Number of Puppies and Weeks of Lactation

Requirements for lactation:
ME (kcal) = maintenance + BW × (24*n* + 12*m*) × *L*
Extrapolated maintenance energy requirements during lactation: 145 kcal × $BW^{0.75}$
ME (kcal) = 145 kcal × $BW^{0.75}$ + BW × (24*n* + 12*m*) × *L*

Where:
BW = body weight of bitch (kg)
n = number of puppies between 1 and 4
m = number of puppies between 5 and 8 (<5 puppies *m* = 0)
L = correction factor for stage of lactation: week 1, 0.75; week 2, 0.95; week 3, 1.1; and week 4, 1.2 (see text)

Example:
Bitch 22 kg, 6 puppies, third week of lactation
Maintenance requirements = $22^{0.75} \times 145$ kcal = 10.16 × 145 kcal = 1,473 kcal
Number of puppies = 6: *n* = 4, *m* = 2,
Stage of lactation third week: *L* = 1.1
Requirements for lactation = 22 × (24 × 4 + 12 × 2) × 1.1 kcal = 2,904 kcal
Total requirements = 1,473 kcal + 2,904 kcal = 4,377 kcal

TABLE 15-8 Nutrient Requirements of Bitches for Late Gestation and Peak Lactation[a]

	Minimal Requirement			Adequate Intake			Recommended Allowance			Safe Upper Limit		
Nutrient	Amt./ kg DM (≡4,000 kcal)[b]	Amt./ 1,000 kcal ME[c]	Amt./ kg $BW^{0.75}$[d]	Amt./ kg DM (≡4,000 kcal)[b]	Amt./ 1,000 kcal ME[c]	Amt./ kg $BW^{0.75}$[d]	Amt./ kg DM (≡4,000 kcal)[b]	Amt./ 1,000 kcal ME[c]	Amt./ kg $BW^{0.75}$[d]	Amt./ kg DM (≡4,000 kcal)[b]	Amt./ 1,000 kcal ME[c]	Amt./ kg $BW^{0.75}$[d]
Crude Protein				200	50	24.6	200	50	24.6			
Amino Acids												
Arginine (g)[e]				10.0	2.50	1.23	10.0	2.50	1.23			
Histidine (g)				4.4	1.10	0.54	4.4	1.10	0.54			
Isoleucine (g)				7.1	1.78	0.87	7.1	1.78	0.87			
Methionine (g)				3.1	0.78	0.38	3.1	0.78	0.38			
Methionine & Cystine (g)				6.2	1.55	0.76	6.2	1.55	0.76			
Leucine (g)				20.0	5.00	2.46	20.0	5.00	2.46			
Lysine (g)				9.0	2.25	1.11	9.0	2.25	1.11			
Phenylalanine (g)				8.3	2.08	1.02	8.3	2.08	1.02			
Phenylalanine & Tyrosine(g)[f]				12.3	3.08	1.51	12.3	3.08	1.51			
Threonine (g)				10.4	2.60	1.28	10.4	2.60	1.28			
Tryptophan (g)				1.2	0.30	0.15	1.2	0.30	0.15			
Valine (g)				13.0	3.25	1.60	13.0	3.25	1.60			
Total Fat (g)				85	21.3	10.5	85	21.3	10.5	330[b]	82.5	40.6
Fatty Acids												
Linoleic Acid (g)				11	2.8	1.4	13	3.3	1.6	65[b]	16.3	8.0
α-Linolenic Acid (g)[g]				0.7	0.18	0.09	0.8	0.2	0.10			
Arachidonic Acid (g)												
Eicosapentaenoic + Docosahexaenoic Acid (g)[h]				0.5	0.13	0.06	0.5	0.13	0.06	11[b]	2.8	1.4
Minerals												
Calcium (g)				8.0	1.9	0.82	8.0	1.9	0.82			
Phosphorus (g)				5.0	1.2	0.58	5.0	1.2	0.58			
Magnesium (mg)				600	150	69	600	150	69			
Sodium (mg)				2,000	500	238	2,000	500	238			
Potassium (g)				3.6	0.9	0.430	3.6	0.9	0.43			
Chloride (mg)				3,000	750	358	3,000	750	358			
Iron (mg)[i]				70	17	8.67	70	17	8.67			
Copper (mg)[i]				12.4	3.1	1.52	12.4	3.1	1.52			
Zinc (mg)				96	24	11.7	96	24	11.7			
Manganese (mg)				7.2	1.8	.87	7.2	1.8	.87			
Selenium (μg)				350	87.5	43	350	87.5	43			

Iodine (µg)		880	220	108	880	220	108			
Vitamins										
Vitamin A (RE)[j]		1,212	303	149	1,515	379	186	15,000[j]	3,750[j]	1,846[j]
Cholecalciferol (µg)[k]		11.0	2.75	1.35	13.8	3.4	1.70	80	20	9.8
Vitamin E (α-tocopherol) (mg)[l]		24	6.0	3.0	30	7.5	3.7			
Vitamin K (Menadione)(mg)[m]		1.3	0.33	0.16	1.6	0.41	0.20			
Thiamin (mg)		1.8	0.45	0.22	2.25	0.56	0.28			
Riboflavin (mg)		4.2	1.05	0.52	5.3	1.3	0.64			
Pyridoxine (mg)		1.2	0.30	0.15	1.5	0.375	0.185			
Niacin (mg)		13.6	3.4	1.67	17	4.25	2.09			
Pantothenic Acid (mg)		12	3.0	1.48	15	3.75	1.84			
Cobalamin (µg)		28	7	3.45	35	8.75	4.3			
Folic Acid (µg)		216	54	26.6	270	67.5	33.2			
Biotin[n]										
Choline (mg)		1,360	340	167	1,700	425	209			

[a]Few data could be found for the dietary concentrations for the minimal requirement for gestation for the bitch. The values for lactation relative to kg DM and 1,000 kcal ME may be taken as satisfactory for gestation.

[b]The values for Amt/kg DM have been calculated assuming a dietary energy density of 4,000 kcal ME/kg. (The term ≡ signifies equivalence.) If the energy density of the diet is not 4,000 kcal ME/kg, then to calculate the Amt/kg DM for each nutrient, multiply the value for the nutrient in the column labeled Amt/kg DM by the energy density of the pet food (in kcal ME/kg) and divide by 4,000.

[c]To calculate the amount to feed of each nutrient, multiply the value for Amt/1,000 kcal ME for each nutrient by the energy requirement in kcal (calculated from Tables 15-6 and 15-7) and divide by 1,000.

[d]The values for Amt/$BW^{0.75}$ apply only to a 22-kg bitch in peak lactation with 8 puppies and consuming 5,000 kcal/day. To calculate the amount for bitches of different body weights or litter sizes, calculate the energy requirement from Table 15-7 and multiply this value by the nutrient Amt/1,000 kcal and divide by 1,000. To calculate the amount of a nutrient for gestating dogs, calculate the energy requirement from Table 15-6, and multiply this value by the nutrient Amt/1,000 kcal and divide by 1,000.

[e]0.01 g arginine should be added for every g of crude protein above 200.

[f]The quantity of tyrosine required to maximize black hair color may be about 1.5-2.0 times this quantity.

[g]The requirement for α-linolenic acid varies depending upon linoleic acid content of the diet. The ratio of linoleic acid to α-linolenic acid should be between 2.6 and 16. Note that 0.8 g/kg DM value shown is the minimum RA of α-linolenic acid at 13 g linoleic acid per kg DM, resulting in a ratio of linoleic acid to α-linolenic acid of approximately 16.

[h]50-60% of the total amount should be eicosapentaenoic, acid and 40-50% should be docosahexaenoic acid.

[i]Some oxides of iron and copper should not be used because of low bioavailability.

[j]Vitamin A requirements expressed as RE (retinol equivalents). One RE is equal to 1 µg of all-*trans* retinol, and one IU of vitamin A is equal to 0.3 RE. Safe upper limit values expressed as µg retinol.

[k]1 µg cholecalciferol = 40 IU vitamin D_3.

[l]Higher concentrations of vitamin E are recommended for high PUFA diets. One international unit of vitamin E = 1 mg all-*rac*-α-tocopheryl acetate (see Chapter 8).

[m]Dogs have a metabolic requirement, but a dietary requirement has not been demonstrated when natural diets are fed. Adequate vitamin K is probably synthesized by intestinal microbes. The vitamin K allowance is expressed in terms of the commercially used precursor menadione that requires alkylation to the active vitamin K.

[n]For normal diets not containing raw egg white, adequate biotin is probably provided by microbial synthesis in the intestine. Diets containing antibiotics may need supplementation.

TABLE 15-9 Daily Metabolizable Energy Requirements for Growth of Kittens After Weaning

ME (kcal) = maintenance amount $\times$ 6.7 $\times$ [$e^{(-0.189p)}$ – 0.66]
ME (kcal) = 100 $\times$ $BW_a^{0.67}$ $\times$ 6.7 $\times$ [$e^{(-0.189p)}$ – 0.66]
Where:

$p = BW_a/BW_m$
BW_a = actual body weight at time of evaluation (kg)
BW_m = expected mature body weight (kg)
e = base of natural log $\approx$ 2.718

Example: Kitten, 1 kg BW_a, 4 kg BW_m
ME (kcal) = 100 $\times$ $1^{0.67}$ $\times$ 6.732 $\times$ [$e^{(-0.189 \times 1/4)}$ – 0.66] = 198 kcal

TABLE 15-10 Nutrient Requirements for Growth of Kittens After Weaning

	Minimal Requirement			Adequate Intake			Recommended Allowance			Safe Upper Limit		
Nutrient	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.67}$[c]	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.67}$[c]	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.67}$[c]	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.67}$[c]
Crude Protein	180	45	9.40				225	56.3	11.8			
Amino Acids												
Arginine (g)[d]	7.7	1.93	0.40				9.6	2.4	0.50	35	8.75	1.83
Histidine (g)	2.6	0.65	0.14				3.3	0.83	0.17	>22	>5.5	>1.15
Isoleucine (g)	4.3	1.08	0.23				5.4	1.4	0.29	>87	>21.7	>4.54
Methionine (g)	3.5	0.88	0.18				4.4	1.1	0.23	13	3.25	0.68
Methionine & Cystine (g)	7.0	1.75	0.37				8.8	2.2	0.46			
Leucine (g)	10.2	2.55	0.53				12.8	3.2	0.67	>87	>21.7	>4.54
Lysine (g)	6.8	1.70	0.35				8.5	2.1	0.44	>58	>14.5	>3.03
Phenylalanine (g)	4.0	1.00	0.21				5.0	1.3	0.27	>29	>7.25	>1.51
Phenylalanine & Tyrosine (g)[e]	15.3	3.83	0.80				19.1	4.8	1.00	68	17	3.55
Threonine (g)	5.2	1.30	0.27				6.5	1.6	0.33	>51	>12.7	>2.66
Tryptophan (g)	1.3	0.33	0.069				1.6	0.40	0.084	17	4.25	0.89
Valine (g)	5.1	1.28	0.27				6.4	1.6	0.33	>87	>21.7	>4.54
Glutamic Acid (g)										75	18.8	3.92
Taurine (g)[f]	0.32	0.080	0.017				0.40	0.10	0.021	>8.9	>2.22	>0.46
Total Fat (g)				90	22.5	4.7	90	22.5	4.7	>330[a]	>82.5	>17.2
Fatty Acids												
Linoleic Acid (g)				5.5	1.4	0.29	5.5	1.4	0.29	55[a]	13.8	2.9
α-Linolenic Acid (g)				0.2	0.05	0.010	0.2	0.05	0.010			
Arachidonic Acid (g)				0.2	0.05	0.010	0.2	0.05	0.001			
Eicosapentaenoic & Docosahexaenoic (g)[g]				0.1	0.025	0.005	0.1	0.025	0.005			
Minerals												
Calcium (g)	5.2	1.3	0.274				8.0	2.0	0.410			
Phosphorus (g)	4.8	1.2	0.251				7.2	1.8	0.372			

Magnesium (mg)	160	40	8.3				400	100	20			
Sodium (mg)	1,240	310	65				1,400	350	74	>10 g		
Potassium (g)	2.68	0.67	0.14				4.0	1.0	0.209			
Chloride (mg)	760	190	42				900	225	46.5			
Iron (mg)[h]	70	17	3.2				80	20	4.2			
Copper (mg)[h]	4.5	1.1	0.23				8.4	2.1	0.44			
Zinc (mg)	50	12.5	2.6				75	18.5	3.9			
Manganese (mg)				4.8	1.2	0.25	4.8	1.2	0.25			
Selenium (µg)	120	30	6.23				300	75	15.8			
Iodine (µg)				1,800	450	93	1,800	450	93			
Vitamins												
Vitamin A (µg retinol)[i]				800	200	42	1,000	250	52	80,000[j]	20,000[j]	4,180[j]
Cholecalciferol (µg)[j]	2.78	0.70	0.14				5.6	1.4	0.29	750	188	39
Vitamin E (α-tocopherol) (mg)[k]				30	7.5	1.6	38	9.4	2.0			
Vitamin K (Menadione) (mg)[l]				1.0	0.25	0.05	1.0	0.25	0.05			
Thiamin (mg)	4.4	1.1	0.23				5.5	1.4	0.29			
Riboflavin (mg)				3.2	0.80	0.17	4.0	1.0	0.21			
Pyridoxine (mg)	2.0	0.5	0.10				2.50	0.625	0.13			
Niacin (mg)				32	8.0	1.7	40	10.0	2.1			
Pantothenic Acid (mg)	4.6	1.15	0.24				5.70	1.43	0.30			
Cobalamin (µg)				18	4.5	0.9	22.5	5.6	1.18			
Folic Acid (µg)	600	150	31				750	188	39			
Biotin (µg)[m]				60	15	3.1	75	18.75	3.9			
Choline (mg)	2,040	510	107				2,550	637	133			

[a]The values for Amt/kg DM have been calculated assuming a dietary energy density of 4,000 kcal ME/kg. (The term ≡ signifies equivalence.) If the energy density of the diet is not 4,000 kcal ME/kg, then to calculate the Amt/kg DM for each nutrient, multiply the value for the nutrient in the column labeled Amt/kg DM by the energy density of the pet food (in kcal ME/kg) and divide by 4,000.

[b]To calculate the amount to feed of each nutrient, multiply the value for Amt/1,000 kcal ME for each nutrient by the energy requirement in kcal for kittens (calculated from Table 15-9) and divide by 1,000.

[c]The values for Amt/$BW^{0.67}$ apply only to 800 g kittens with an expected mature body weight of 4 kg. To calculate the amounts for kittens of different actual or expected mature body weights, calculate the energy requirement from Table 15-9 and multiply this by the nutrient Amt/1,000 kcal and divide by 1,000.

[d]0.02 g arginine should be added for every g of crude protein above 180 g and 225 g for the MR and RA, respectively.

[e]To maximize black hair color, an equal quantity or greater of tyrosine to that of phenlyalanine is required.

[f]The recommended allowance of taurine for highly digestible purified diets is 0.4 g/kg diet, whereas the allowances for dry expanded and canned diets are 1.0 g and 1.7 g/kg DM, respectively.

[g]It is advised that eicosapentaenoic acid not exceed 60% of the total eicosapentaenoic + docosahexaenoic amount.

[h]Some forms of iron and copper should not be used because of low bioavailability.

[i]One IU of vitamin A is equal to 0.3 µg of all-*trans* retinol or 1 µg retinol = 3.333 IU of vitamin A. Safe upper limit values expressed as µg retinol.

[j]1 µg cholecalciferol = 40 IU vitamin D_3.

[k]Higher concentrations of vitamin E are recommended for high PUFA diets. One international unit of vitamin E = 1 mg all-*rac*-α-tocopheryl acetate (see Chapter 8).

[l]Cats have a metabolic requirement, but a dietary requirement has not been demonstrated when natural diets (except fish-based diets) are fed. Under most conditions, adequate vitamin K is probably synthesized by intestinal microbes. The vitamin K allowance is expressed in terms of the commercially used precursor menadione that requires alkylation to the active vitamin K.

[m]For normal diets not containing raw egg white, adequate biotin is probably provided by microbial synthesis in the intestine. Diets containing antibiotics may need supplementation.

TABLE 15-11 Daily Metabolizable Energy Requirements for Adult Cats at Maintenance[a]

Type	Metabolizable Energy Requirement
Domestic cats, lean[b]	100 kcal × kg $BW^{0.67}$
Domestic cats, overweight[c]	130 kcal × kg $BW^{0.4}$
Exotic cats	55-260 kcal × kg $BW^{0.75}$

[a]Requirements of individual cats may be over- or underestimated by more than 50%.
[b]Body condition scores (Table 3-7) ≤ 5 on a 9-point scale.
[c]Body condition scores (Table 3-7) > 5 on a 9-point scale.

TABLE 15-12 Nutrient Requirements of Adult Cats for Maintenance

	Minimal Requirement			Adequate Intake			Recommended Allowance			Safe Upper Limit		
Nutrient	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.67c}$	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.67c}$	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.67c}$	Amt./ kg DM (≡4,000 kcal)[a]	Amt./ 1,000 kcal ME[b]	Amt./ kg $BW^{0.67c}$
Crude Protein	160	40	3.97				200	50	4.96			
Amino Acids												
Arginine (g)[d]				7.7	1.93	0.19	7.7	1.93	0.19			
Histidine (g)				2.6	0.65	0.064	2.6	0.65	0.064			
Isoleucine (g)				4.3	1.08	0.11	4.3	1.08	0.11			
Methionine (g)[e]	1.35	0.34	0.033				1.7	0.43	0.042			
Methionine & Cystine (g)	2.7	0.68	0.067				3.4	0.85	0.084			
Leucine (g)				10.2	2.55	0.25	10.2	2.55	0.25			
Lysine (g)	2.7	0.68	0.067				3.4	0.85	0.084			
Phenylalanine (g)				4.0	1.00	0.099	4.0	1.00	0.099			
Phenylalanine & Tyrosine (g)[f]				15.3	3.83	0.38	15.3	3.83	0.38			
Threonine (g)				5.2	1.30	0.13	5.2	1.30	0.13			
Tryptophan (g)				1.3	0.33	0.032	1.3	0.33	0.032			
Valine (g)				5.1	1.28	0.13	5.1	1.28	0.13			
Taurine (g)[g]	0.32	0.080	0.0079				0.40	0.10	0.0099			
Total Fat (g)				90	22.5	2.2	90	22.5	2.2	330[a]	82.5	8.2
Fatty Acids												
Linoleic Acid (g)				5.5	1.4	0.14	5.5	1.4	0.14	55[a]	13.8	1.4
α-Linolenic Acid (g)												
Arachidonic Acid (g)				0.02	0.005	0.0005	0.06	0.015	0.0015	2[a]	0.5	0.049
Eicosapentaenoic & Docosahexaenoic Acid (g)[h]				0.1	0.025	0.0025	0.1	0.025	0.0025			
Minerals												
Calcium (g)	1.6	0.40	0.040				2.9	0.72	0.071			
Phosphorus(g)	1.4	0.35	0.035				2.6	0.64	0.063			
Magnesium (mg)	200	50	4.9				400	100	9.5			
Sodium (mg)	650	160	16.0				680	170	16.7	>15 g		
Potassium (g)				5.2	1.3	0.13	5.2	1.3	0.13			
Chloride (mg)				960	240	23.7	960	240	23.7			

Iron (mg)[i]				80	20	1.98	80	20	1.98			
Copper (mg)[i]				5.0	1.2	0.119	5.0	1.2	0.119			
Zinc (mg)				74	18.5	1.9	74	18.5	1.9	>600		
Manganese (mg)				4.8	1.2	0.119	4.8	1.2	0.119			
Selenium (µg)				300	75	6.95	300	75	6.95			
Iodine (µg)	1,300	320	31.6				1,400	350	35			
Vitamins												
Vitamin A (µg retinol)[j]				800	200	19.8	1,000	250	24.7	100,000[j]	25,000[j]	2,469[j]
Cholecalciferol (µg)[k]				5.6	1.4	0.14	7	1.75	0.17	750	188	19
Vitamin E (α-tocopherol) (mg)[l]				30	7.5	0.74	38	10	0.94			
Vitamin K (Menadione) (mg)[m]				1.0	0.25	0.025	1.0	0.25	0.025			
Thiamin (mg)				4.4	1.1	0.11	5.6	1.4	0.14			
Riboflavin (mg)				3.2	0.80	0.079	4.0	1.0	0.099			
Pyridoxine (mg)	2.0	0.5	0.05				2.50	0.625	0.06			
Niacin (mg)				32	8.0	0.79	40	10.0	0.99			
Pantothenic Acid (mg)	4.6	1.15	0.11				5.75	1.44	0.14			
Cobalamin (µg)				18	4.5	0.44	22.5	5.6	0.56			
Folic Acid (µg)	600	150	15				750	188	19			
Biotin (µg)[n]				60	15	1.5	75	18.75	1.9			
Choline (mg)	2,040	510	50				2,550	637	63			

[a]The values for Amt/kg DM have been calculated assuming a dietary energy density of 4,000 kcal ME/kg. (The term ≡ signifies equivalence.) If the energy density of the diet is not 4,000 kcal ME/kg, then to calculate the Amt/kg DM for each nutrient, multiply the value for the nutrient in the column labeled Amt/kg DM by the energy density of the pet food (in kcal ME/kg) and divide by 4,000.

[b]To calculate the amount to feed of each nutrient, multiply the value for Amt/1,000 kcal ME for each nutrient by the energy requirement for lean cats in kcal ME (calculated from Table 15-11) and divide by 1,000. For cats with an unusually low energy intake (below the suggested requirement), the nutrient concentrations (Amt/1,000 kcal) may not be adequate. These animals should be fed the nutrient amounts shown in the column Amt/kg $BW^{0.67}$.

[c]The values in Amt/$BW^{0.67}$ have been calculated for a lean cat with an energy intake of 100 kcal × $BW^{0.67}$. To calculate the amounts for adult cats that are not lean, calculate the energy requirements from Table 15-11 and multiply this value by the nutrient Amt/1,000 kcal and divide by 1,000.

[d]0.02 g arginine should be added for every g of crude protein above 200 g for the RA of arginine.

[e]Methionine presumed to be one-half the sum of the requirement for methionine + cystine combined.

[f]To maximize black hair color, an equal quantity or greater of tyrosine to that of phenylalanine is required.

[g]The recommended allowance of taurine for highly digestible purified diets is 0.4 g/kg diet, whereas the allowances for dry expanded and canned diets are 1.0 and 1.7 g/kg diet, respectively.

[h]Includes docosahexaenoic acid only; no information is available on eicosapentaenoic acid. It is advised that eicosapentaenoic acid is included but not exceed 20% of the total eicosapentaenoic + docosahexaenoic amount.

[i]Some oxides of iron and copper should not be used because of low bioavailability.

[j]One IU of vitamin A is equal to 0.3 µg of all-*trans* retinol or 1 µg retinol =3.333 IU of vitamin A. Safe upper limit values expressed as µg retinol.

[k]1 µg cholecalciferol = 40 IU vitamin D_3.

[l]Higher concentrations of vitamin E are recommended for high PUFA diets. One international unit of vitamin E = 1 mg all-*rac*-α-tocopheryl acetate (see Chapter 8).

[m]Cats have a metabolic requirement, but a dietary requirement has not been demonstrated when natural diets (except fish-based diets) are fed. Under most conditions, adequate vitamin K is probably synthesized by intestinal microbes. The vitamin K allowance is expressed in terms of the commercially used precursor menadione that requires alkylation to the active vitamin K.

[n]For normal diets not containing raw egg white, adequate biotin is probably provided by microbial synthesis in the intestine. Diets containing antibiotics may need supplementation.

TABLE 15-13 Daily Metabolizable Energy Requirements for Lactating Queens

Kittens	Energy Requirement
<3	ME kcal = maintenance + 18 × BW × *L* ME kcal = 100 × $BW^{0.67}$ + 18 × BW × *L*
3-4	ME kcal = maintenance + 60 × BW × *L* ME kcal = 100 × $BW^{0.67}$ + 60 × BW × *L*
>4	ME kcal = maintenance + 70 × BW × *L* ME kcal = 100 × $BW^{0.67}$ + 70 × BW × *L*

L = factor for stage of lactation from week 1 to week 7: 0.9, 0.9, 1.2, 1.2, 1.1, 1.0, 0.8

Example: Queen, 3.5 kg BW at mating, 4 kittens, peak lactation (week 3)
ME kcal = 100 × $3.5^{0.67}$ + (60 × 3.5 × 1.2) = 231 + 252 = 483 kcal

TABLE 15-14 Nutrient Requirements of Queens in Late Gestation and Peak Lactation[a]

	Minimal Requirement			Adequate Intake			Recommended Allowance			Safe Upper Limit		
Nutrient	Amt./ kg DM (≡4,000 kcal)[b]	Amt./ 1,000 kcal ME[c]	Amt./ kg $BW^{0.67}$[d]	Amt./ kg DM (≡4,000 kcal)[b]	Amt./ 1,000 kcal ME[c]	Amt./ kg $BW^{0.67}$[d]	Amt./ kg DM (≡4,000 kcal)[b]	Amt./ 1,000 kcal ME[c]	Amt./ kg $BW^{0.67}$[d]	Amt./ kg DM (≡4,000 kcal)[b]	Amt./ 1,000 kcal ME[c]	Amt./ kg $BW^{0.67}$[d]
					Gestating Adult Cats							
Crude Protein	170	43	5.90				213	53	7.40			
Amino Acids												
Arginine (g)[e]				15	3.75	0.52	15	3.75	0.52			
Histidine (g)				4.3	1.08	0.15	4.3	1.08	0.15			
Isoleucine (g)				7.7	1.93	0.27	7.7	1.93	0.27			
Methionine (g)				5.0	1.25	0.170	5.0	1.25	0.170			
Methionine & Cystine (g)				9.0	2.25	0.31	9.0	2.25	0.31			
Leucine (g)				18	4.50	0.63	18	4.50	0.63			
Lysine (g)				11	2.75	0.38	11	2.75	0.38			
Phenylalanine (g)												
Phenylalanine & Tyrosine(g)[f]	15.3	3.83	0.53				19.1	4.78	0.66			
Threonine (g)				8.9	2.23	0.31	8.9	2.23	0.31			
Tryptophan (g)				1.9	0.48	0.066	1.9	0.48	0.066			
Valine (g)				10	2.50	0.35	10	2.50	0.35			
Taurine (g)[g]	0.42	0.105	0.015				0.53	0.13	0.018			
					Lactating Adult Cats							
Crude Protein	240	60	12.9				300	75	16.10			
Amino Acids												
Arginine (g)[e]				15	3.8	0.81	15	3.8	0.81			
Histidine (g)				7.1	1.8	0.39	7.1	1.8	0.39			
Isoleucine (g)				12	3.0	0.64	12	3.0	0.64			
Methionine (g)				6.0	1.5	0.32	6.0	1.5	0.32			
Methionine & Cystine (g)				10	2.6	0.56	10.4	2.6	0.56			
Leucine (g)				20	5.0	1.07	20	5.0	1.07			
Lysine (g)				14	3.5	0.75	14	3.5	0.75			
Phenylalanine (g)												
Phenylalanine & Tyrosine (g)[f]	15.3	3.83	0.52	0.82			19.1	4.8	1.03			
Threonine (g)				10.8	2.7	0.58	10.8	2.7	0.58			
Tryptophan (g)				1.9	0.48	0.100	1.9	0.48	0.100			

Taurine (g)[g]	0.42	0.105	0.015				0.53	0.13	0.018			
Total Fat (g)				90	22.5	4.8	90	22.5	4.8	330[b]	82.5	17.6
Fatty Acids												
Linoleic Acid (g)				5.5	1.4	0.3	5.5	1.4	0.3	55[b]	13.8	2.93
α-Linolenic Acid (g)				0.2	0.050	0.011	0.2	0.05	0.011			
Arachidonic Acid (g)				0.2	0.050	0.011	0.2	0.050	0.011			
Eicosapentaenoic & Docosahexaenoic Acid (g)[h]				0.1	0.0250	0.0067	0.1	0.025	0.0044			
Minerals												
Calcium (g)				10.8	2.7	0.565	10.8	2.7	0.565			
Phosphorus (g)	4.9	1.22	.261				7.6	1.9	0.411			
Magnesium (mg)	416	104	22				500	125	32			
Sodium (mg)				2,680	670	142	2,680	670	142			
Potassium (g)				5.2	1.3	.277	5.2	1.3	0.277			
Chloride (mg)				4,000	1,000	213	4,000	1,000	213			
Iron (mg)[i]				80	20	4.3	80	20	4.3			
Copper (mg)[i]				8.8	2.2	0.47	8.8	2.2	0.47			
Zinc (mg)	42	10.5	2.2				60	15	3.2			
Manganese (mg)				7.2	1.8	0.38	7.2	1.8	0.38			
Selenium (µg)				300	75	16	300	75	16			
Iodine (µg)				1,800	450	96	1,800	450	96			
Vitamins												
Vitamin A (µg retinol)[j]				1,600	400	85	2,000	500	107	100,000[j]	25,000[j]	5,333[j]
Cholecalciferol (µg)[k]				5.6	1.4	0.30	7.0	1.75	0.37	750	188	40
Vitamin E (α-tocopherol) (mg)[l]				30	7.5	1.6	31	7.8	1.67			
Vitamin K (Menadione) (mg)[m]				1.0	0.25	0.18	1.0	0.25	0.18			
Thiamin (mg)				5.0	1.25	0.27	6.3	1.56	0.32			
Riboflavin (mg)				3.2	0.80	0.17	4.0	1.0	0.21			
Pyridoxine (mg)	2.0	0.5	0.10				2.50	0.625	0.11			
Niacin (mg)				32	8.0	1.71	40	10.0	2.10			
Pantothenic Acid (mg)	4.6	1.15	0.25				5.75	0.19	0.31			
Cobalamin (µg)				18	4.5	0.80	22.5	5.6	1.0			
Folic Acid (µg)	600	150	27				750	187	33			
Biotin (µg)[n]				60	15	2.7	75	18.75	3.3			
Choline (mg)	2,040	510	91				2,550	637	113			

[a]With the exception of amino acids, few data could be found for the dietary concentrations for the minimal requirement for gestation for the queen. For other nutrients, the values for lactation relative to kg DM and 1,000 kcal ME may be taken as satisfactory for gestation and lactation in the queen.

[b]The values for Amt/kg DM have been calculated assuming a dietary energy density of 4,000 kcal ME/kg. (The term ≡ signifies equivalence.) If the energy density of the diet is not 4,000 kcal ME/kg, then to calculate the Amt/kg DM for each nutrient, multiply the value for the nutrient in the column labeled Amt/kg DM by the energy density of the pet food (in kcal ME/kg) and divide by 4,000.

[c]To calculate the amount to feed of each nutrient, multiply the value for Amt/1,000 kcal ME for each nutrient by the energy requirement in kcal ME (calculated from Table 15-13 for a lactating cat, or by multiplying kg $BW^{0.67}$ by 140 for a cat during gestation) and divide by 1,000.

[d]The values for Amt/$BW^{0.67}$ only apply to a queen weighing 4 kg in peak lactation with 3-4 kittens consuming 540 kcal ME/day. If the queen does not fit these criteria, calculate the ME requirement from Table 15-13, multiply this value by nutrient Amt/1,000 kcal and divide by 1,000. To calculate the nutrient requirements for late gestation, compute the energy requirements from 140 × kg $BW^{0.67}$ and multiply by Amt/1,000 kcal and divide by 1,000.

[e]0.02 g arginine should be added for every g of crude protein above 170 g and 213 g for the MR and RA, respectively.

[f]To maximize black hair color, an equal quantity or greater of tyrosine to that of phenylalanine is required.

[g]The recommended allowance of taurine for highly digestible purified diets is 0.53 g/kg DM, whereas the allowances for dry expanded and canned diets are 1.0 and 1.7 g/kg dietary DM, respectively.

[h]It is advised that eicosapentaenoic acid not exceed 60% of the total eicosapentaenoic + docosahexaenoic amount.

[i]Some oxides of iron and copper should not be used because of low bioavailability.

[j]One IU of vitamin A is equal to 0.3 µg of all-*trans* retinol or 1 µg retinol = 3.333 IU of vitamin A. Safe upper limit values expressed as µg retinol.

[k]1 µg cholecalciferol = 40 IU vitamin D_3.

[l]Higher concentrations of vitamin E are recommended for high PUFA diets. One international unit of vitamin E = 1 mg all-*rac*-α-tocopheryl acetate (see Chapter 8).

[m]Cats have a metabolic requirement, but a dietary requirement has not been demonstrated when natural diets (except fish-based diets) are fed. Under most conditions, adequate vitamin K is probably synthesized by intestinal microbes. The vitamin K allowance is expressed in terms of the commercially used precursor menadione that requires alkylation to the active vitamin K.

[n]For normal diets not containing raw egg white, adequate biotin is probably provided by microbial synthesis in the intestine. Diets containing antibiotics may need supplementation.

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Appendix A

About the Authors

Donald C. Beitz, Ph.D. (*Chair*) is Charles F. Curtiss Distinguished Professor of Agriculture since 1989 in the Departments of Animal Science and of Biochemistry, Biophysics and Molecular Biology at Iowa State University, where he has taught since 1967. His expertise lies primarily in comparative nutrition, with an emphasis in human and domestic animal nutrition, biochemistry, and molecular biology. His research interests focus on lipid and vitamin metabolism. He is currently involved in research on the oral use of *Eubacterium coprostanoligenes* to decrease blood cholesterol in animals and humans; use of glucagon to prevent and treat bovine fatty liver; influence of vitamin D on meat tenderness; and genetic and nutritional regulation of fatty acid composition of meat and milk. Beitz has served as both a member (1990-1994) and chair (1995-1998) of NRC's Committee on Animal Nutrition. He also served as a member of the NRC Briefing Panel on Biotechnology in Agriculture (1985). In addition to numerous university-wide committees, Beitz also has served as a member and officer in professional societies such as the American Society for Nutritional Sciences (formerly American Institute of Nutrition), the American Society of Animal Science, American Dairy Science Association, American Society of Biochemistry and Molecular Biology, Comparative Nutrition Society, and various U.S. Department of Agriculture advisory committees. Beitz received his B.S. (1962) in agricultural science and his M.S. (1963) in dairy science both from the University of Illinois. He received his Ph.D. in dairy nutrition and biochemistry from Michigan State University in 1967.

John E. Bauer, Ph.D., D.V.M. is professor of small animal medicine and surgery and holder of the Mark L. Morris Professorship of Clinical Nutrition in the College of Veterinary Medicine at Texas A&M University. He is the immediate past chair of the Intercollegiate Graduate Faculty of Nutrition at Texas A&M. Bauer's areas of specialization are lipid biochemistry, disorders of lipid metabolism, and comparative biomedicine and nutrition. His studies have included lipoprotein and fatty acid metabolism of domestic and exotic animals as well as animal models of hypercholesterolemia and atherogenesis of humans. He has written over 230 peer-reviewed and other publications, is the recipient of numerous grants, awards, and honors and is listed in American Men and Women of Science, and Who's Who in Veterinary Science and Medicine. He has received several Outstanding Paper Presentation Awards from the American Oil Chemists' Society and C. E. Cornelius Young Investigator Research Award from the University of Florida. Bauer has chaired and has been an active member on several committees on animal nutrition over the past 20 years. Bauer received his D.V.M. from University of Illinois as well as his M.S. and Ph.D. in nutritional sciences.

Keith Behnke, Ph.D. is professor in the Department of Grain Science and Industry at Kansas State University where he has been a member of the faculty since 1971. He currently coordinates all feed processing research and the production of all research feeds manufactured by the Department of Grain Science and Industry. Prior to his position at Kansas State University, Behnke was a group leader in processing research of the food division of Far Mar, Co., in Hutchison, KS. Behnke is currently a member of several professional societies and associations, some of which include the American Society of Animal Science, Poultry Science Association, American Feed Industry Association, and the Chinese Feed Manufacturing Association, of which he is an honorary member. Behnke received his B.S. in feed technology (1968), his M.S. in grain science (1973), and his Ph.D. in grain science (1975) from Kansas State University.

David A. Dzanis, D.V.M., Ph.D. is owner of Dzanis Consulting and Collaborations, which provides post-product development consulting services on matters related to veterinary nutrition and regulation including services for interpreting state and federal laws, federal and state labeling issues, and compliance in marketing claims. Prior to be-

ginning full-time work as a consultant in 1998, Dzanis spent eight years in the Food and Drug Administration's Center for Veterinary Medicine of the Department of Health and Human Services as a veterinary nutritionist. He is currently a contributing editor for *Petfood Industry* and was editor-in-chief for *Veterinary Clinical Nutrition*. He has served as chairman of the Association of American Feed Control Official's Feline Nutrition Expert Subcommittee and Canine Nutrition Expert Subcommittee. Dzanis has also served in various capacities as a member of the American College of Veterinary Nutrition (Diplomate 1990), American Academy of Veterinary Nutrition, and American Veterinary Medical Association. Awards and honors received include the FDA Group Recognition Award in 1998, Association of American Feed Control Official's Distinguished Service Award in 1994, FDA Commissioner's Special Citation in 1992, FDA Commendable Service Award in 1991, and the ALPO/ American Veterinary Medical Association Foundation's Fellowship in Veterinary Nutrition in 1984. Dzanis has published scientific and lay articles. He received his D.V.M. from Purdue University and his Ph.D. from Cornell University.

George C. Fahey, Jr., Ph.D. is professor of animal sciences and nutritional sciences and assistant dean, Office of Research, Agricultural Experiment Station, College of Agricultural, Consumer and Environmental Sciences, University of Illinois, Urbana-Champaign. Fahey's specific areas of research include companion animal nutrition, oligosaccharides and resistant starches, and plant cell wall structure and its effects on nutrition of animals and humans. Fahey has served on several editorial boards (*Journal of Animal Science, Journal of Nutrition, Journal of Dairy Science, Archives of Animal Nutrition, Journal of Animal Physiology and Animal Nutrition*). Fahey has served as chairman, secretary, and as a member of numerous committees in the animal science and nutrition fields. Fahey has worked with the NRC on many occasions; he was a member of Committee on Animal Nutrition, Subcommittee on Laboratory Animal Nutrition, and Subcommittee on Establishing a North American Feed Information System. Some of the many awards and honors received by Fahey include the Companion Animal Biology Award from the American Society of Animal Science in 2003, the Distinguished Alumnus award from West Virginia University College of Agriculture, Forestry and Family Resources in 1997, Senior Faculty Award for Excellence in Research from College of Agricultural, Consumer and Environmental Sciences at University of Illinois at Urbana-Champaign in 1996, Distinguished Service Award from Farmland Industries in 1994, Pioneer Hi-Bred International, Inc. Forage Award from American Dairy Science Association in 1992, and American Feed Industry Association Award for Ruminant Nutrition Research in 1990. Fahey received his M.S. in agricultural biochemistry and his Ph.D. in animal nutrition from West Virginia University.

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Appendix B

Acronyms and Abbreviations

AA	amino acid
AA, 20:4n-6	arachidonic acid
AAFCO	Association of American Feed Control Officials
ACTH	adrenocorticotropic hormone
ADF	acid detergent fiber
ADP	adenosine diphosphate
AI	adequate intake
ALA	α-linolenic acid
AMP	adenosine monophosphate
AOAC	American Organization of Analytical Chemists
ARAT	aryl-CoA retinol acyltransferase
Arg	arginine
As	arsenic
Asp	aspartic acid
ATP	adenosine triphosphate
ATPase	adenosine triphosphatase
B	boron
BCKAD	branched-chain α-ketoacid dehydrogenase
BCS	body condition score
BHA	butylated hydroxyanisole
BHT	butylated hydroxytoluene
BMR	basal metabolic rate
BNF	British Nutrition Foundation Task Force on Fatty Acids
BV	biological value
BW	body weight
°C	degrees Celsius
Ca	calcium
$CaCl_2$	calcium chloride
$CaCO_3$	calcium carbonate
cal	calories
CASPER	computer-assisted spectrum evaluation of regular polysaccharides
CCK	cholecystokinin
CCK-PZ	cholecystokinin-pancreozymin
CD4+	cell-surface glycoprotein found on the mature helper T cells and immature thymocytes, as well as on monocytes and macrophages
CDNA	complementary DNA
CE	capillary electrophoresis
CEL	cellulose
CFU	colony forming units
CFR	Code of Federal Regulations
Cl^-	chloride ion
CLA	conjugated linoleic acid
CO	cyclooxygenase
CoA	coenzyme A
CP	crude protein
Cr	chromium
CRABP	cellular retinoic acid-binding protein
CRALBP	cellular retinaldehyde-binding protein
CRBP	cellular retinal-binding protein
Cu	copper
CVM	Center for Veterinary Medicine
d	day
Da	dalton
DBG	dried brewer's grain
DBP	vitamin D binding protein
DCM	dilated cardiomyopathy
DDGS	distiller's dried grains with solubles
DE	digestible energy
DF	dietary fiber
DGLA, 20:3n-6	dihomogammalinolenic acid
DHA, 22:6n-3	docosahexaenoic acid
dL	deciliter
DM	dry matter
DMG	dimethylglycine
DNA	deoxyribosnucleic acid
DP	degree of polymerization
DPA, 22:5n-3	docosapentaenoic acid
DSHEA	Dietary Supplement Health and Education Act

dTMP	deoxythymidine monophosphate
dUMP	deoxyuridine monophosphate
EAP	endogenous acid production
EDTA	ethylenediaminetetracetic acid
EFA	essential fatty acid
EGR	erythrocyte glutathione reductase
EGRAC	EGR activity coefficient
EPA, 20:5n-3	eicosapentaenoic acid
EPOC	excess post-exercise oxygen consumption
ERABP	epididymal retinoic acid-binding protein
ERG	electroretinogram
E:T	essential amino acid nitrogen to total amino acid nitrogen
ETKA	ethryocyte transketolase activity
°F	degrees Fahrenheit
FA	fatty acids
FAD	flavin-adenine dinucleotide
FCRD	feline central retinal degeneration
FDA	U.S. Food and Drug Administration
Fe	iron
FFA	free fatty acid
FIGLU	formiminoglutamic acid
Fio_2	fractional concentration of oxygen in inspired air
FIRI	fasting insulin resistance index
FMN	flavin mononucleotide
g	gram
GAG	glycosaminoglycans
GE	gross energy
GI	gastrointestinal
GIP	gastric inhibitory peptide
GLA	γ-linolenic acid
GLC	gas-liquid chromatography
GLP-1	glucagon-like peptide-1
GLP-2	glucagon-like peptide-2
Glu	glutamic acid
GLUT-5	Na^+-independent glucose transporter system
Gly	glycine
GP	glycogen phosphorylase
GRAS	generally recognized as safe
GRP	gastrin-releasing peptide
GSH-Px	glutathione peroxidase
h	hour
ha	hectare
HCl	hydrochloric acid
HCM	high-cellulose mixture
HCO	hydrogenated coconut oil
HDL	high-density lipoprotein
Hg	mercury
His	histidine
HPAEC	high-performance anion exchange chromatography
HPLC	high-performance liquid chromatography
$H_4PteGlu_n$	tetrahydrofolate with *n* glutamic acid residues
5-HT	5-hydroxytryptamine
I	iodine
IF	intrinsic factor
Ig	immunoglobulin
IL-2	interleukin-2
Ile	isoleucine
IU	international unit
IVF	induced viscosity fiber
K	potassium
kcal	kilocalories
K_d	disassociation constant
kJ	kilojoules
K_m	Michaelis constant
L	liter
LA	linoleic acid
LACFR	low acid canned food regulations
lb	pound
LCAT	lecithin-cholesterol acyltransferase
LCM	low-cellulose mixture
LCPUFA	long-chain polyunsaturated fatty acid
LD_{50}	median lethal dose
LDL	low-density lipoprotein
LES	lower esophageal sphincter
Leu	leucine
LO	lipoxygenase
LTB_4	leukotriene B_4
LTB_5	leukotriene B_5
LTQ	lysine tyrosylquinone
LUTD	lower urinary tract disease
Lys	lysine
m	meter
m^3	cubic meter
MCT	medium-chain triacylglycerol
ME	metabolizable energy
MEK	methionine enkephalin
MER	maintenance energy requirement
Met	methionine
mg	milligram
Mg	magnesium
MK	menaquinone
mL	milliliter
mm	millimeter
MMC	migrating motor complex
mmol	millimole
Mn	manganese
Mo	molybdenum
MR	minimal requirement
n*, *N	number
Na	sodium
NADH	nicotinamide-adenine dinucleotede
NAE	net urinary acid excretion
NAG	*N*-acetylglutamate

NDF	neutral detergent fiber
NE	net energy
NFE	nitrogen-free extract
Ni	nickel
NMB	neuromedin
nmol	nanomole
NPU	net protein utilization
NRC	National Research Council
NSHP	nutritional secondary hyperparathyroidism
NSP	non-starch polysaccharide
OCD	osteochondritis dissecans
P	phosphorus
PAD	pulsed amperometric detection
PAI	presumed adequate intake
PCr	phosphocreatine
PED	pulsed electrochemical detection
PEG	polyethylene glycol
PER	protein efficiency ratio
PGE_2	prostaglandin E_2
Phe	phenylalanine
PIVKA	protein involved with vitamin K absence
PLP	pyridoxal 5′-phosphate
PO_4^{3-}	phosphate
PP	pancreatic polypeptide
P-P factor	pellagra-preventive factor
PQQ	pyrroloquinoline quinone
PTH	parathyroid hormone
PUFA	polyunsaturated fatty acid
RA	recommended allowance
RAR	retinoic acid receptor
RBC	red blood cell (erythrocyte)
RBP	retinol-binding protein
RDI	recommended dietary intake
RE	retinol equivalents
RFMR	resting fed metabolic rate
RNA	ribonucleic acid
ROS	reactive oxygen species
RQ	respiratory quotient
RS	resistant starch
RXR	retinoid X receptor
S	sulfur
SAMe	*S*-adenosylmethionine
SBF	sugar beet fiber
SCFA	short-chain fatty acid
SCN	suprachiasmatic nucleus
SD	standard deviation
SDH	succinate dehydrogenase
Se	selenium
SF	soluble fiber
Si	silicon
SO_4^{2-}	sulfate
SUL	safe upper limit
T_3	3,5,3′-triiodothyronine
T_4	thyroxine
TAT	tyrosine aminotransferase
TBARS	thiobarbituric acid reducing substance
TBHQ	tertiary butylhydroquinone
TDF	total dietary fiber
TE	tocopherol equivalent
Thr	threonine
TMP	thiamin monophosphate
TPN	total parenteral nutrition
TPP	thiamin pyrophosphate
TR	thyroid receptor
tRNA	transfer RNA
Try	tryptophan
TTA	tryptophan tryptophylquinone
TTP	thiamin triphosphate
U	unit
USP	United States Pharmacopeia
UWL	unstirred water layer
V	vanadium
$\dot{V}O_{2max}$	maximal oxygen capacity
$\dot{V}O_{2rest}$	oxygen consumption at rest
Val	valine
VDR	vitamin D receptor
VESRD	vitamin E-selenium responsive disease
VIP	vasoactive intestinal polypeptide
VLDL	very low density lipoprotein
wt	weight
y	year
Zn	zinc

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