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Role of carbohydrates in the health of dogs

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Health has become one of the most important factors for dog owners when choosing a diet for their pets.[1] This growing consciousness in health has resulted in a large number of pet foods that boast various claims. Often, these claims mimic trends in human nutrition.[1] Low-carbohydrate, high-protein diets have become increasingly popular for both humans and pets.[2–4] An increasing number of pet owners believe that dietary carbohydrates are unnecessary and may even be harmful.[3] Obesity, diabetes mellitus, cancer, adverse food reactions, and gastrointestinal diseases are common medical concerns for dogs.[5–10] Diet, and carbohydrates in particular, plays an important role in the treatment of these conditions. The intent of the information reported here is to provide an overview of dietary carbohydrates in canine nutrition and examine the role of dietary carbohydrates in the treatment of obesity, diabetes mellitus, cancer, and adverse food reactions in dogs. The role of carbohydrates in gastrointestinal health has been reviewed elsewhere.[11–13]

Carbohydrate Classification

Carbohydrates are broadly classified as simple or complex on the basis of their chemical structure **(Figure 1)**.[14] Monosaccharides are the simplest form of carbohydrates and cannot be further broken down by enzymatic digestion. Complex carbohydrates (oligosaccharides and polysaccharides) consist of 3 to 10 or > 10 sugar units, respectively.[14] Starch, the most abundant digestible carbohydrate found in plants, contains glucose molecules bound together by α-glycosidic bonds, which undergo enzymatic digestion by α-amylase in the small intestine of mammals.[14–16] Dietary fibers are complex carbohydrates that resist enzymatic digestion in the mammalian small intestine owing to β-glycosidic bonds between the sugar units.[14] Dietary fibers are derived from polysaccharides in plant cell walls and can be classified in several ways on the basis of their rate of fermentation by intestinal microbiota, solubility within the colon, and chemical structure.[14,15]

Carbohydrate Digestion, Absorption, and Metabolism in Dogs

Carbohydrate digestion in dogs starts with mechanical breakdown of food within the oral cavity. However, because of the extremely limited production of salivary α-amylase in dogs, enzymatic digestion does not commence in the mouth.[17] Instead, α-amylase is released by the pancreas in dogs, which allows efficient digestion of starch in the small intestine.[18] Pancreatic α-amylase in dogs is sensitive to the quantity of starch in the diet; α-amylase activity will increase with increasing amounts of dietary starch.[19,20] Extruded canine diets containing 35% to 40% DM of starch in the form of barley, corn, potato, rice, sorghum, or wheat all have starch digestibility > 99%.[21]

Once starch is digested, glucose and galactose are actively transported across the mucosal brush border of the small intestines by SGLT1.[15] Dogs express the T1R2/T1R3 heterodimer within the sweet receptor of the tongue, which is necessary for the regulation of SGLT1; thus, it is suggested that dogs are able to upregulate SGLT1 in response to the amount of dietary carbohydrates consumed.[22] Dogs reportedly have a glucose absorption rate similar to that of humans.[23]

Energy needs of the body greatly influence the metabolic fate of dietary glucose. Once glucose is absorbed, it can be used for ATP production through glycolysis, stored in the liver and skeletal muscles as glycogen, or converted to fat and stored as adipose tissue.[14,15] Glucokinase or hexokinase (or both) are necessary for the first rate-limiting step in glycoly-

ABBREVIATIONS

DM	Dry matter
ME	Metabolizable energy
NRC	National Research Council
SGLT1	Sodium-dependent glucose transporter-1

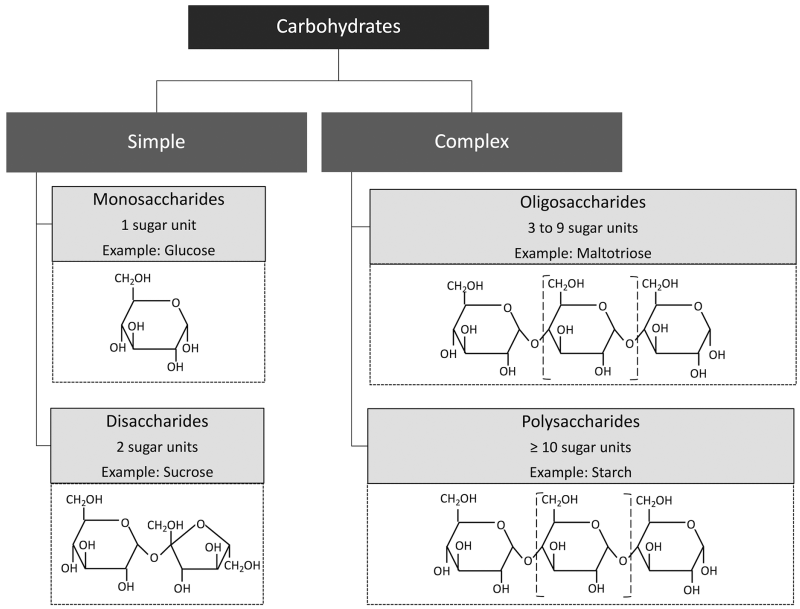

Figure 1—Schematic diagram depicting the classification of carbohydrates into simple and complex categories on the basis of chemical structure and degree of polymerization. Simple carbohydrates consist of monosaccharides and disaccharides that contain 1 and 2 sugar units, respectively. Complex carbohydrates include oligosaccharides and polysaccharides that contain 3 to 10 or > 10 sugar units, respectively. Notice for oligosaccharides and polysaccharides that the indicated middle unit (dashed lines) would be repeated 1 to 7 times and > 7 times, respectively.

sis, wherein glucose is phosphorylated to produce glucose-6-phosphate.[14,15] Glucokinase is found in the liver and pancreatic β cells. In contrast to hexokinase, glucokinase is not inhibited by its product glucose-6-phosphate and has a high affinity for glucose, which allows it to be effective when there is an abundance of glucose. As a result, the liver is able to respond appropriately to the consumption of a starch-rich meal and high blood glucose concentrations.[15] The activity of glucokinase in dogs increases in a fed state,[21] which means that glucose oxidation is upregulated postprandially.[16] Storage of excess dietary glucose as glycogen is vital for maintaining homeostasis of blood glucose. Breakdown of these glycogen reserves allows for the endogenous release of glucose when blood concentrations decrease (eg, during periods when food is withheld), which is critical for maintaining blood glucose homeostasis.[14]

Dietary Carbohydrate Requirements and Self-selected Intake

Dogs do not have a dietary requirement for carbohydrate, except during pregnancy and lactation.[24,25] However, dogs have a metabolic requirement for glucose. Similar to other species, certain tissues and cells (eg, brain and RBCs) rely on glucose for energy needs.[15] Carbohydrates in pet foods provide a valuable and important source of glucose, but if carbohydrates are provided in insufficient amounts, protein can provide animals with glucose through gluconeogenic pathways. However, consuming dietary carbohydrates provides metabolic benefits by allowing the body to use the carbohydrates as an energy source so that protein can be used for other important anabolic processes (eg, growth, tissue repair, and the immune response). Protein is also a less efficient energy source than carbohydrates because of the requirement for the body to excrete the nitrogenous waste that is a by-product of amino acid gluconeogenesis.[14]

The metabolic need for glucose in dogs is especially important during gestation and lactation to support increased demands for energy. The use of carbohydrate-free diets during gestation has resulted in adverse consequences, including an increased mortality rate of puppies as well as hypoglycemia and acetonemia in bitches.[24,25]

Dietary fiber is also not considered an essential requirement for dogs. However, the addition of fiber to the diet helps to maintain a healthy gastrointestinal tract, promotes regular bowel movements, regulates pH within the colon, and contributes to the growth of beneficial bacteria within the gastrointestinal tract.[26] Because dietary fiber is not digested by mammalian enzymes, it provides minimal energy to an animal; thus, fiber can be used to reduce energy density of the diet to help promote weight management.[27,28]

The ratio of protein, fat, and carbohydrate that dogs will naturally select when provided free-choice access to foods with various macronutrient ratios has been a topic of interest. In a controlled environment, dogs selected a low-carbohydrate diet with 7% of ME from carbohydrate, 30% of ME from protein, and 63% of ME from fat.[29] It is unknown whether this macronutrient balance promotes optimal health of dogs or can be attributed to taste preference. Although this ratio differs substantially from the recommended allowance of protein (8.8% of ME) and fat (12.4% of ME) established by the NRC,[30] it should be mentioned that the values recommended by the NRC are minimum recommendations and do not necessarily support optimal health. In a recent study,[31] investigators assessed the food choices of dogs when the factor of flavor was removed and palatability was balanced among the foods provided. In that study,[31] dogs typically selected foods with 36% of ME from carbohydrate, 30% of ME from protein, and 41% of ME from fat. Although the percentages of fat and protein selected again were higher than the values recommended by the NRC, the percentage of carbohydrate was comparable to the quantities found in commercial extruded foods formulated for dogs.[32]

Carbohydrate Content in Evolutionary Diets

Pet dogs are descended from wolves. Investigators of 1 study[33] determined that the adaptation to a starch-rich diet was a crucial step in the early domestication of modern dogs. The authors of that study[33] performed whole genomic sequencing of dogs and wolves and identified 36 unique genomic regions that contained 122 genes belonging to dogs. Specifically, 10 genes were identified as having key roles in starch digestion and fat metabolism. Additionally, dogs had greater expression of the pancreatic amylase gene and higher activity of that enzyme, compared with results for wolves. Therefore, this evidence indicated that dogs have evolved to digest dietary starch much more efficiently than do gray wolves.[33] This is suggested to be a result of the availability of starch-rich food and waste to which ancestors of modern-day dogs grew accustomed as they became domesticated and the genetic adaptations that followed as a result of the consumption of a starch-rich diet.[33] However, the proportion of plant matter consumed by wolves can range from 0% to 50% of the overall diet,[34–36] which would suggest that wolves can also metabolize substantial amounts of dietary starch and fiber.

Carbohydrates in Conventional Dry and Wet Dog Foods

Dry pet food comprises the largest share of pet food sold in North America (approx 72% of sales).[37] Results of a survey published in 2008 indicate that > 80% of dog owners in the United States and Australia fed their dogs at least half of their diet in the form of a commercial dry food.[38] More recently, another survey found that 61% of dogs were fed a commercial dry food daily.[39] It is believed that extruded dry food is preferred by dog owners because of the convenience, wide variety of products, and economical price.[38,40,41] Carbohydrates play a key functional role in extruded kibble by helping create structural integrity.[42] To account for the allowance of protein and fat recommended by the NRC, conventional foods formulated for adult dogs can contain up to 78.8% of ME as carbohydrates. Wet foods also contain carbohydrates to achieve the desired amount of gelatinization and texture,[43] although wet foods often contain a smaller percentage of carbohydrates than do extruded kibbles.[32]

Carbohydrates in the Development and Treatment of Conditions

Carbohydrates have an important role in the development as well as the treatment of several conditions in dogs.

Obesity

Obesity is the most common nutritional disorder affecting dogs. The population of overweight and obese dogs has been estimated as 17% to 44% in developed countries.[5,44–51] The main contributor to obesity is a positive energy balance (ie, energy consumed is greater than energy expended).[52] Certain diseases and pharmaceuticals may also contribute to the development of obesity. In a 2010 study,[53] it was reported that 97% of veterinary practices attributed owner-specific factors (eg, lack of exercise and overfeeding) as the cause of obesity in dogs.

Starch consumed in excess of an animal's immediate energy requirements will be stored as glycogen or converted to body fat.[14] Contrary to popular belief, the conversion of dietary carbohydrates to body fat is inefficient in humans, even when carbohydrates are consumed in large quantities.[54] The conversion of dietary carbohydrates to fat (and storage as body fat) requires much more energy, compared with that required for the storage of dietary fats.[55,56] Additionally, because the body's glycogen stores are small, oxidation of carbohydrates is adjusted to match the intake of carbohydrates by an individual person. In comparison, oxidation of fat is not primarily regulated on the basis of intake.[54] Data on conversion of dietary carbohydrates to body fat in dogs are not available. Overall, despite the increasing proportion of overweight and obese dogs, little has been published on the topic of carbohydrates and their influence on weight gain. In 1 study,[57] adult dogs fed a high-fat diet (51% of ME from fat and 29% of ME from carbohydrate) gained almost twice the amount of body fat, compared with results for those on a high-carbohydrate diet (23% of ME from fat and 59% of ME from carbohydrate) when food was provided ad libitum. However, dogs fed the high-fat diet also consumed 13% more energy. This was likely attributable to the higher energy density of the high-fat diet and positive influence of dietary fat on palatability. Diets with a higher energy density allow dogs to reach daily energy requirements with a smaller food volume, which causes them to be more likely to consume excess amounts of energy.[58,59]

In humans, a diet with a high glycemic load or that is rich in starch with a high glycemic index may predispose individuals to a higher risk of weight gain and obesity because these foods may have a less satiating effect.[60–63] Only a few studies[64,65] have been conducted to test the glycemic index of carbohydrate sources for dogs. Additionally, to the authors' knowledge, no studies have been conducted to investigate the impact of the glycemic index or glycemic load on body weight, body composition, or satiety of dogs. Therefore, information regarding starch and its implications in obesity or satiety of dogs is lacking.

Carbohydrate is often vilified as contributing to weight gain or preventing weight loss, and protein is touted as a beneficial macronutrient for weight loss. Thus, high-protein, low-carbohydrate diets, such as the Atkins diet,[66] have remained popular as weight-loss diets for humans. Rate of weight loss or time to reach target body weight did not differ significantly between obese dogs fed a high-protein, low-starch diet (protein, 47.5% DM; starch, 5.3% DM) and a medium-protein, medium-starch control diet (protein, 23.8% DM; starch, 23.9% DM), both of which were fed at 40% to 55% of the dogs' maintenance energy requirements.[67] However, the authors of that study[67] suggested that high protein content in a weight-loss diet may better conserve lean body mass.

Furthermore, there is a large amount of evidence to support the beneficial effects of dietary fiber for overweight and obese humans.[68] The consumption of dietary fiber increases the amount of bulk in the gastrointestinal tract, which allows individuals to feel satiated sooner and thereby limit the quantity of food consumed. Soluble fiber also contributes to delayed gastric emptying and slower transit of food through the small intestine, which further promotes satiation.[15] Additionally, dietary fiber may be beneficial for weight loss because it reduces the energy density of the diet and may reduce the efficiency of the gastrointestinal tract to digest macronutrients and extract energy.[69] There have been inconsistent results regarding the role of dietary fiber in weight loss of dogs.[70–76] These inconsistencies likely stem from the variety of sources and quantities of dietary fiber investigated. However, the inclusion of dietary fiber in weight-loss diets for dogs has provided greater effects on satiation, reductions in body fat, a higher percentage of weight loss, and reductions in voluntary energy intake.[71,73,75–77]

Diabetes mellitus

Diabetes mellitus is an endocrine disorder that results in hyperglycemia because of insufficient insulin production or decreased insulin sensitivity. The prevalence of diabetes in dogs is believed to have increased during the past 40 years.[6] It is estimated that 1.2% of dogs will develop diabetes mellitus before they are 2 years old.[7] The autoimmune destruction of β cells, as occurs in humans with type 1 diabetes mellitus, is a common feature of diabetes mellitus in dogs.[78] The development of diabetes mellitus in dogs is believed to be a multifactorial phenomenon and can be influenced by a variety of environmental and genetic factors (eg, breed and sex).[7,8,79,80] A large proportion of dogs with diabetes mellitus also have pancreatitis.[81–87] Thus, it is thought that damage to the pancreatic β cells as a result of chronic or acute pancreatitis could lead to the development of diabetes mellitus in dogs.

Because dogs most commonly develop diabetes mellitus that resembles type 1 diabetes mellitus in humans, carbohydrate intake is generally not considered a risk factor in the pathogenesis of the disease in dogs. Thus, the likelihood that carbohydrate intake will lead to diabetes mellitus in dogs is less of a concern, in contrast to humans and cats, which may develop type 2 diabetes mellitus as a result of chronic hyperglycemia and insulin resistance.[88] The authors are not aware of any studies that have been conducted to investigate the relationship between carbohydrate intake and the development of diabetes mellitus in dogs. However, because pancreatitis has been identified as a potential risk factor for the development of diabetes mellitus in dogs,[81–87] the amount of fat in a diet should be considered for dogs with both pancreatitis and diabetes mellitus.

Chronic consumption of diets with a low glycemic index or glycemic load by humans has been linked to improved glucose control, insulin sensitivity, and an overall lower risk of developing diabetes mellitus.[63,89,90] However, as previously mentioned, there is currently a paucity of studies on the effects of the glycemic index and glycemic load in dogs. Few studies have focused on glycemic response. Investigators of 1 study[91] found that the starch content of commercial dog foods has a substantial impact on postprandial glucose concentrations, although the starch sources of the diets were not reported. In addition, feeding pulses or foods that have a low glycemic index (eg, peas and lentils) for humans may also result in a reduced glycemic response in dogs. Feeding of such pulses can cause delayed and prolonged glycemic and insulinemic responses when used as a single ingredient or included in extruded diets.[32,64,65] However, the potential physiologic benefits of long-term feeding of diets with a low glycemic index or glycemic load and impacts on the development of diabetes mellitus in dogs currently are unknown.

Veterinarians often consider dietary carbohydrate intake for dogs with diabetes mellitus. Dietary starch intake can be a major determinant of the postprandial glycemic response, regardless of the type of carbohydrate, carbohydrate source, or diet macronutrient profile.[91] However, reducing the percentage of carbohydrate in a diet can increase the percentage of fat, which may be contraindicated for diabetic dogs. High-fat diets and hypertriglyceridemia are possible causes of pancreatitis,[92,93] and subclinical pancreatitis is difficult to identify in diabetic dogs.[94] Dietary fat may also diminish insulin sensitivity and predispose animals to weight gain.[57,95] Therefore, it is prudent to consider a diet with low to moderate amounts of fat for all diabetic dogs. In contrast to simply reducing carbohydrate intake, day-to-day consistency in carbohydrate intake in conjunction with insulin treatment is a key component for the management of dogs with diabetes mellitus.[96] In general, foods containing ≤ 55% digestible carbohydrate (DM basis) are acceptable for dogs with diabetes mellitus, especially in conjunction with dietary fiber supplementation.[97–99] Additionally, modification to the type of carbohydrate in a diet may be considered (including avoiding simple sugars) as well as the addition of dietary fiber to a diet.[100] In contrast to simple sugars, starch must be broken down and digested before it is absorbed. As a result, the postprandial glucose and insulin responses after the consumption of these complex carbohydrates will be lower, compared with the responses after ingestion of simple sugars.[101]

The role of dietary fiber in the management of diabetes mellitus in dogs has been extensively evaluated. The viscosity of fiber allows it to impair and slow the absorption of dietary glucose into the blood, which results in reduced glycemic responses.[43,102–104] Both diabetic and healthy dogs have lower blood glucose concentrations and smaller fluctuations in blood glucose concentrations when fed diets with a higher percentage of fiber, which may help to maintain blood glucose homeostasis.[105,106] Fiber sources investigated have included soluble (ie, guar gum, pectin, and carboxymethyl cellulose) and insoluble (ie, cellulose) fiber.[98,107] However, the role of dietary fiber in improving long-term disease outcomes in diabetic dogs has not been evaluated.

Cancer

Nutrition plays a key role in the prevention and management of cancer. It is estimated that 25% of dogs develop cancer at some point during their lifetime.[8] However, research concerning nutrition and cancer in dogs is limited. The effects of carbohydrates on cancer in humans have been an emerging topic of investigation as a result of the altered glucose metabolism in malignant cells.

Because many types of cancer cells rely on glycolysis for energy demands,[108–110] the role of simple carbohydrates in the development and progression of cancer has been of special interest. Specifically, hyperglycemia leading to hyperinsulinemia has been investigated to determine effects on cancer progression and survival rates.[111–115] Research concerning insulin and malignant cell proliferation in vitro has revealed a positive correlation,[115] but in vivo data in mice have not provided conclusive evidence of a positive effect.[116–118] The authors are not aware of any similar studies on carbohydrate metabolism and cancer in dogs.

Alterations in macronutrient metabolism have been detected for both human and canine cancer patients.[118–123] Because cancer cells rely on anaerobic metabolism for energy needs, simple carbohydrates are converted into lactate.[124] Consequently, dogs with lymphoma have higher insulin and lactate concentrations, compared with concentrations in healthy dogs, even after remission following chemotherapy.[120,121] As a result, a diet containing a lower concentration of simple carbohydrates and higher concentrations of protein and fat has been suggested for dogs with cancer.[125] Effects of diet on energy expenditure and cancer cachexia in dogs have been evaluated.[126] In that study,[126] dogs with lymphoma received isocaloric amounts of a high-fat (36.87% DM) or high-carbohydrate (58.10% DM) diet. Although the authors reported no significant effect of diet on energy expenditure, conclusions on diet efficacy could not be drawn for this study because analyses of survival time and remission duration were not performed. Similarly, there have been no clinically relevant findings regarding the potential of low-carbohydrate diets for the treatment of cancer in humans.[127,128]

Adverse food reactions

Adverse food reactions can be described as an abnormal response to the ingestion of a specific food or ingredient.[129] Adverse food reactions can be categorized as nonimmunologic (ie, dietary intolerances) or immunologic (ie, dietary allergies or hypersensitivities).[129] The prevalence of adverse food reactions among dogs admitted to dermatology referral centers ranges from 7.6% to 12%.[10,130] Of dogs with adverse food reactions, 9% to 30.6% have clinical signs compatible with atopy.[10,130,131] Similarly, a systematic review of the literature revealed that common gastrointestinal signs (eg, vomiting and diarrhea) occurred in > 20% of dogs and cats with adverse food reactions.[132] There is a paucity of published studies regarding the prevalence of adverse food reactions in the general population of dogs because adverse food reactions often mimic clinical signs of other diseases and can often coexist with other types of allergies, such as environmental allergies and flea bite allergies.[133]

Any dietary protein can potentially be allergenic; however, the most commonly reported food allergens for dogs include beef, dairy, chicken, and wheat.[134,135] Carbohydrates typically are not a concern as an allergen, but the protein in carbohydrate-rich products (eg, wheat or soy) typically used in the manufacture of pet food can be responsible for adverse food reactions in some animals.[134–136] It has been estimated that wheat and soy are responsible for 13% to 15%[135,136] and 6%[135,136] of adverse food reactions in dogs, respectively.

Similar to the situation in humans, gluten intolerance may also affect dogs. However, gluten intolerance in dogs is extremely rare and has been well described in only 2 families of Irish Setters.[137] Gluten intolerance is linked to the protein fraction of some grains, rather than to the starch or carbohydrate fraction. More specifically, gluten intolerance arises because of the alcohol-soluble protein known as gliadin found within gluten. Gliadin can be found in wheat, barley, and rye.[138] The exact prevalence of gluten intolerance in Irish Setters as well as the general population of dogs remains unknown. The cause for the development of gluten intolerance in these dogs also warrants further investigation,[139,140] although it has been speculated that an increase in mucosal permeability may play a role in the condition.[139,141,142]

Inadequate activity of intestinal disaccharidase, as occurs during lactose intolerance, can also affect dogs. Clinical signs of disaccharide intolerance in dogs are similar to those in humans and include diarrhea and bloating.[143] Disaccharide intolerance results from a lack of disaccharidase activity in the intestinal brush border and may occur as a result of rapid dietary changes or enteritis.[144] Consequently, a transition period of several days is recommended when changing diets fed to dogs to allow for the adaptation to other carbohydrate sources and alterations in their respective disaccharidase activities.[144]

Modification of the amount of carbohydrate in diets is typically not required for the management of adverse food reactions.[144] However, choosing a highly digestible or novel carbohydrate source is often recommended. Highly digestible carbohydrates may be beneficial for patients because of the possibility of malabsorption resulting from inflammation in the gastrointestinal tract.[144]

Clinical Summary

Despite the large number of dog owners who are averse to feeding carbohydrates to their pets, there is little evidence to support the contention that any negative health effects result from feeding diets that provide dietary carbohydrates in amounts (30% to 60% DM) commonly found in commercial extruded pet foods. There appears to be no association between dietary carbohydrate and the development of obesity, diabetes mellitus, cancer, or adverse food reactions in dogs. In fact, dogs appear to have evolved so that they can metabolize substantial quantities of carbohydrate. Increasing the amount of complex carbohydrates in diets results in the reduction of dietary protein or fat (or both), which may provide benefits for dogs with certain conditions, such as obesity, diabetes mellitus with concurrent pancreatitis, or adverse food reactions.

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