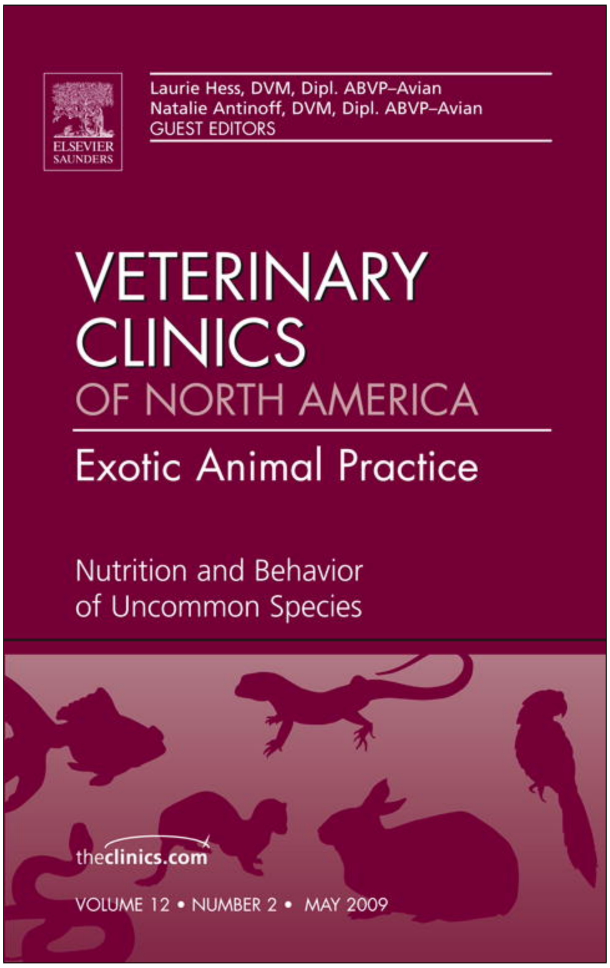
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Feeding Behavior and Nutrition of the Sugar Glider (*Petaurus breviceps*)

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KEYWORDS

• Feeding • Gliders • Gumivore • Nutrition • Marsupial

Despite the popularity of sugar gliders (*Petaurus breviceps*) as a companion species in the United States, and a more extensive history of captive management in its native Australia as well as in zoologic institutions globally, a number of health issues potentially related to suboptimal dietary husbandry are still reported, including malnutrition, obesity, osteodystrophy, vitamin and mineral imbalances, and dental disease.[1,2] Physiologic requirements for energy and nitrogen determined for sugar gliders should be taken into consideration when developing feeding programs. Until more detailed requirements are established for other nutrients, nutritional principles for provision of balanced diets should be extrapolated from other species models, incorporating, if possible, life-history habits of this unique marsupial.

FEEDING BEHAVIORS

Sugar gliders (*Petaurus breviceps*) are nocturnal, omnivorous, arboreal marsupials that feed on a variety of plant and insect exudates and arthropods, with natural diet dependent on habitat characteristics and season. They have an elongated fourth digit to extract insects from bark, as well as enlarged lower incisors to chew into bark. Several studies of feeding ecology[3–6] in different locations in Australia indicate that diet is highly correlated with resource availability, and that sugar gliders are remarkably adaptable. Direct observations and fecal analysis in a 1-year study determined specific feeding activities, including feeding on *Acacia* spp gum and on sap (*Eucalyptus* spp), licking branches for honeydew (see below), peeling bark for arthropods, searching foliage for manna (see below), or randomly moving through eucalypts while catching flying insects and large foliage-dwelling insects.[3] During spring and summer, gliders fed mainly on insects and spiders (40%–60% of time), even though exudates were most abundant, possibly to meet increased protein needs associated with

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reproduction. During autumn and winter, gliders spent most time consuming gum, sap, honeydew, and manna (a sweet mucilaginous secretion produced by plants in response to insect damage). Saps and gums were consumed year round and formed the staple diet.

In other studies of other glider colonies,[4,6] primary feeding activity focused on consuming *Banksia* and *Eucalyptus* flowers for nectar (energy) and pollen (protein) for much of the year, even when insects were abundant. Only in autumn did pollen incidence in feces decrease; pollen feeding directly correlated with flowering seasons, and gliders may be an important native pollinator. Sap and arthropods were important foods when flowers were not available. Gliders have been reported to strip the wings and legs off insects before consumption and to forage for insects on the ground.

Gum sites consist of holes made by insects into which gum accumulates; gliders often enlarge these holes using their incisors. Gliders also use incisors to strip bark and create sap-feeding sites by gouging into the phloem (nutrient transport) columns. Such behaviors may be important for maintaining tooth and gum health and should be encouraged, using natural materials such as nontoxic tree branch materials (ie, various branches with either smooth or rough bark). Gliders lick honeydew from branches and beneath bark and harvest manna from new leaves and flower buds through close examination, smelling, and licking. Cage furnishings that allow these natural feeding behaviors and food presentation can provide important environmental enrichment.

NATIVE DIETARY CONSTITUENTS

Plant exudates consumed by free-ranging sugar gliders include nectar, sap, manna, and gums. Additionally, sugar gliders consume insect exudates, such as honeydew and lerp, excess sugars excreted by sap-eating insects on the surface of leaves and small branches. All exudates that have been measured contain low protein content (<1% dry weight[7,8]). Nectars and saps comprise simple sugar solutions that, in general, also contain low concentrations of vitamins and minerals; manna is derived from sap in response to insect damage on tree branches and leaves. Gums are complex carbohydrates: plant polysaccharides that form gels in water. Gums, produced by trees in response to insect and mechanical damage, are refractive to digestive enzymes but fermentable by microbial populations.[9] Gums produced by some Australian *acacia* sp are chemically similar to those found in African *Acacia senegal* trees used for commercial production of gum arabic.[7] Gum acacia has been shown to contain 1% (dry weight) calcium and offsets the lack of calcium in arthropods eaten by the Senegal bush baby.[10] In this respect, it would be valuable to know if mineral content of gums is similar between African and Australian acacias, such that gum arabic might provide a suitable, available substitute feed for gliders. Phloem-feeding insects, such as aphids, scale insects, and psyllids, consume large quantities of sap to meet their nitrogen (protein) requirements and excrete honeydew or lerp on the surface of leaves and small branches. Clearly, the abundance of some of these food sources for sugar gliders is dependent on fluctuating insect populations, as well as on seasonal flow of saps.

Arthropods important as protein sources in sugar glider diets include moths, spiders, and scarabaeid beetles.[3,4] Information on specific nutrient composition of these native arthropods is not available. Nonetheless, most feeder insects that have been analyzed are deficient in calcium relative to phosphorus[10,11] and in specific amino acids.[11] Arachnid invertebrates (spiders) may be an exception, as they contain elevated levels of taurine, a sulfur-containing amino acid.[12]

Pollen is also a source of dietary protein for sugar gliders; 34% of *Eucalyptus* pollen grains in feces were empty, as compared with 66% to 71% from *Banksia* pollen,[4,5] with the contents presumably digested in the small intestine, rather than in the stomach.

DIGESTIVE PHYSIOLOGY

Anatomically, sugar gliders, unlike other arboreal possums but similar to other mammalian gumivores,[7] have an enlarged cecum well-suited for microbial fermentation of complex dietary carbohydrates, such as gums. However, this assumption has not yet been investigated experimentally.

Basal metabolic rate measured in 128-g (g) captive sugar gliders is reported at 209 kJ $kg^{-0.75}$ per day^{-1}, or about 45 kJ per day^{-1} (11 kcal per day^{-1}).[13] Field metabolic rate has also been measured in sugar gliders at about 153 kJ per day^{-1} (approximately 37 kcal) for a 112-g female and 192 kJ per day^{-1} (approximately 46 kcal) for a 135-g male,[14] about four-times basal metabolic rate. Normal captive activity energy requirements might thus be calculated at around two-times basal metabolic rate, or between 76.5 kJ and 96 kJ per day^{-1} (18 kcal–23 kcal) for animals averaging approximately 124 g, although some studies suggest higher energy expenditures than this theoretical minimum.[7] A recent feeding trial comparing three diets in young, growing males averaging 96 g found animals consumed 100.1 kJ to 147 kJ (24 kcal–35 kcal) per day^{-1}.[2] Sugar gliders do not hibernate but can display shallow daily torpor periods, with a drop in body temperature from about 35°C, to 11°C to 28°C for several hours, accompanied by decreases in metabolic rate to 10% to 60% of basal metabolism, mainly in response to food restriction.[15]

Sugar gliders fed honey-pollen diets containing 1.0%, 3.1%, or 6.5% protein, on a dry basis, had maintenance nitrogen requirements determined at 87 mg $kg^{-0.75}$ per day^{-1}, or about 248-mg crude protein for a 100-g animal.[16] Gliders displayed low nitrogen losses in both feces and urine, which may be related to low metabolic rates, overall, or to efficient use of a potentially limited resource. Based on these laboratory studies, free-ranging males are likely able to meet minimal protein requirements with diets comprised of exudates alone, but females must supplement with pollen or arthropods to meet demands of reproduction. Amino acid balance in pollens and native insects feeding on natural vegetation may also be superior to amino acid balance in commercial products and in cultured insects used as substitute foods; thus, this difference should be investigated.[7,11]

In feeding trials conducted with common mixed diets containing 19% to 26% crude protein (dry basis), 96-g growing gliders consumed 1,330-mg to 2,270-mg protein per day (with approximately 70% digestibility). Although most animals gained weight during the 60-day trial period, differences were apparent across dietary treatments, and two of nine animals (on the same diet) actually lost weight, suggesting amino acid balance may have varied considerably across diets.[2] Gliders may have consumed excess protein to meet specific amino acid requirements; unfortunately, amino acids were not measured, and further investigations are needed.

Sugar gliders do not require particularly high-protein diets, and excessive protein may, in fact, be detrimental to overall health; refining amino acid balance and overall level is critical for understanding and providing optimal protein nutrition. In this respect, use of a properly balanced dry or canned commercial product that also includes vitamins and minerals essential for other omnivorous species (ie, dogs or primates) is superior to protein sources comprised of unsupplemented animal products, such as meat, eggs, and insects.

DIETS COMMONLY USED IN FEEDING CAPTIVE SUGAR GLIDERS

A number of Internet Web sites provide information on sugar glider diets, including modifications of an artificial nectar/protein mix originally formulated for Leadbeater's possums (*Gymnobelideus leadbeateri*) composed of water, honey, hard-boiled egg, high-protein human baby cereal, and vitamin and mineral supplements.[1] Nutritionally balanced, commercially available products developed for other species have been fed successfully in zoo and private glider colonies, including dog and cat foods, as well as diets targeted specifically for insectivores, primates, birds, and omnivores. Several diets developed for sugar gliders are available, although no published information on intake or use of these products is currently available. In addition to the dry or semi-moist feedstuffs listed above, a mixture of various fresh fruits and vegetables is offered, with or without added powdered vitamin/mineral supplements, as well as limited live prey (primarily mealworms, *Tenebrio molitor*; wax worms, *Galleria mellonella*; or crickets, *Acheta domesticus*). Treat-items fed range from hard-boiled eggs (with or without shell), to raw or cooked meat, day-old chicks, baby-food meat products, tofu, honey, nonsugared cereals, applesauce, breads, and monkey biscuits. A variety of supplemental liquids are also fed to gliders, including fruit juices and nectars (with or without added vitamin and mineral supplements), nutritionally balanced nectar products, and electrolyte drinks.

No single diet or combination has been determined optimal for captive sugar gliders. A recent study of three commonly offered diet combinations compared intake, digestion, and selectivity.[2] Diets were comprised of:

(A) 15-g Insectivore Fare (Reliable Protein Products, Ranch Mirage, California), 15-g mixed vegetables, 15-g assorted fruits and berries, with added vitamin/mineral supplements (1:1 mix RepCal) (Rep-Cal Research Labs, Los Gatos, California) and Vionate (Gimborn Pet Specialties, LLC, Atlanta, Georgia); and 1-g mealworms or chicken protein source (1.8 g daily average).

(B) 15-g soaked dry cat kibble, 15-g mixed vegetables, 15-g assorted fruits and berries, 0.5-g Frugivore Salad Supplement (HMS Diets, Bluffton, Indiana), and 0.4-g mealworms.

(C) 15-g homemade formulation, 15-g mixed vegetables, 15-g assorted fruits and berries, and 0.3-g mealworms.

Gliders consumed 30% to 40% of body weight daily, approximately 7% to 8.5% in dry matter, and showed distinct preferences for specific foods. In this study, meats (chicken and mealworms) and fruit mixes were preferred, (76%–100% consumption), followed by basal diet (41%–95% consumed), with vegetables least selected (38%–51% consumption). Total diets were highly digestible (73%–79%); crude protein ranged from 19% to 26%, and fat from 6% to 14% (dry basis). Optimal dietary calcium to phosphorus (Ca:P), however, was not achieved with any diet. Calcium deficiency leading to tetany has been reported in gliders.[1] Deficiencies have been linked with diets high in fruits and insects, preferred food items that can be poor calcium sources; hence, this mineral must be supplemented. It appears, however, that current diets, in general, may be over-supplemented with calcium.

Target ratios of Ca:P (1:1–2:1) were met only in Diet B (soaked kibble diet), at 0.7%:0.7% (dry basis). Diet A, as prepared, contained 6.5 times more calcium than phosphorus and, as eaten, 10 times more calcium than phosphorus (2.0% Ca, 0.2% P). Similarly, diet C contained seven to eight times more calcium than phosphorus (3.5% Ca, 0.5% P). Although absolute calcium requirements of sugar gliders are unknown, based on the needs of other animals, a value between 0.5% to 1% of dry matter is estimated for this species, with a dietary phosphorus requirement between 0.2% and 0.5%.[17] Diet B appears too high in phosphorus relative to calcium, whereas Diets A and C both appear too low. Bone quality appeared radiographically normal in all gliders during the course of this short investigation. Nonetheless, circulating levels of 25-hydroxyvitamin D were found to be low in gliders fed Diets A and C, as compared with Diet B (53 ng/mL, 18 ng/mL, and 70 ng/mL, respectively); thus, even this short-term diet may have affected calcium, phosphorus, and vitamin D metabolism. Calculated vitamin D levels in RepCal -supplemented diets (Diet A, 28 IU/g; Diet C, 34 IU/g) were elevated, as compared with Diet B (1.3 IU/g). Although sugar gliders' dietary vitamin D requirement has not yet been determined, for many other species, dietary vitamin D levels are recommended between 0.5 IU/g to 1.5 IU/g of dry matter.[17] Soft-tissue mineralization, indicating potential vitamin D toxicosis, were not noted with any diet in this study. Nonetheless, vitamin D metabolism needs to be investigated in more detail in this species, and all supplements should be used judiciously.

Elevated circulating iron concentrations were also noted in glider blood samples from the feeding trial,[2] possibly indicating excess dietary iron. Iron is a common contaminant of calcium supplements and can lead to oxidative damage and iron storage disease at high levels. Although iron storage disease has not been reported in sugar gliders, evidence of tissue iron deposition has been seen in gliders at necropsy (Debra Thomas, DVM, personal communication, 2003). Sugar gliders do not require dietary vitamin C, as they can synthesize this nutrient,[7] and dietary vitamin C increases absorption of iron. By calculation, all diets in the study appeared to supply more iron and vitamin C than sugar gliders need (87-mg/kg, 175-mg/kg, and 292-mg/kg iron, and 212-mg/kg, 222-mg/kg, and 260-mg/kg vitamin C for Diets A, B, and C, respectively), which may contribute to the observations noted. Thus, the possibility of iron overload may be worth investigating in more detail in captive gliders.

FEEDING RECOMMENDATIONS

Adult captive sugar gliders weighing 130 g require between approximately 76 kJ and 147 kJ (18 kcal–35 kcal) per day to meet maintenance energy requirements, containing less than 500-mg crude protein, depending on protein quality. Fresh food should be offered daily in as-fed amounts, approximately 25% to 30% of body weight, (wet basis, containing approximately 75% water), or approximately 7% to 9% dry-matter intake.[2,17] As a broad rule of thumb, a mixture of one-part dry or semi-moist commercial product to two-parts (by weight) mixed fruits and vegetables (three-quarter fruits, one-quarter vegetables), meets sugar glider's energy and protein needs. If animals are particularly active or are at increased physiologic stages (growth, reproduction), increase the portion of commercial product, rather than the produce, up to one-part dry or semi-moist to one-part produce. If the basal diet is nutritionally complete and consumed in these proportions, there should be little need for additional supplementation. All foods should be high quality; consumption of preferred food items (insects, fruits) should be closely monitored and restricted, such that consumption of balanced calories from the commercial portion of the diet is assured.

An adequate sample daily diet is comprised of:

5-g dry or 10-g semi-moist cat food
5-g berries
5-g citrus

5-g other fruit
5-g sweet potato
1-g mealworm (or other invertebrates, such as grasshoppers, moths, fly pupae, crickets; optional)

Such a diet provides 126 kJ energy, 21% crude protein (1,750 mg), 0.77% calcium, 0.64% phosphorus, vitamin D 1.1 IU/g with this particular (dry generic) cat food.

Another adequate sample diet,[18] blended into a slurry, contains:

12-g chopped, mixed fruit (any type, <10% citrus)
2.5-g cooked, chopped vegetables
10-g peach or apricot nectar
5.5-g ground, dry, low-iron bird diet
1-g mealworm (or other invertebrates, as above; optional)

This diet provides 159 kJ energy, 17% crude protein (1,550 mg), 0.61% calcium, 0.44% phosphorus, and vitamin D 0.9 IU/kg.

From a crude-protein perspective, dry dog, avian, or primate foods lower in protein (approximately 15%–25% dry basis) than cat foods (approximately 30%–45% protein) could be used to meet the protein requirements of sugar gliders. Fruits and vegetables can be frozen and thawed; however, canned fruits packed in syrup or processed baby foods ideally should not be used. Fresh produce is preferred, particularly fruits and vegetables that contain more calcium than phosphorus (ie, berries, citrus, figs, papaya, or flower blossoms). Minimize use of fruits with inverse Ca:P ratios (ie, grapes, bananas, apples, pears, melon). Information on mineral balance can be found on the United States Department of Agriculture Nutrient Database (http://www.nal.usda.gov/fnic/foodcomp/search). Feeder insects should be healthy and maintained on a gut-loaded diet before feeding to gliders. Treat items also must be carefully controlled to prevent obesity. Three grams (one-half teaspoon) of unsupplemented applesauce, for example, provides up to 7% of daily calculated energy needs for a 130-g sugar glider; such treats should be factored in as part of the daily total dietary produce allotment.

Fresh water should always be available and changed at least daily; gliders can drink from sipper bottles. The use of nutritionally balanced nectar products for liquid feeding is preferred over the use of diluted fruit juices, fruit nectars, or electrolyte solutions. Caloric contributions of liquid feeds must also be factored into daily energy calculations. In addition, gliders should be weighed and body condition assessed regularly.

AREAS FOR FURTHER INVESTIGATION

To complete an understanding of sugar glider's dietary needs, several areas still need to be investigated:

Mineral content of native Acacia gums consumed by gliders should be quantified.
Methods and products to increase gum feeding by captive gliders must be developed to enhance digestive function, as well as to highlight natural behaviors.
Sugar glider's ability to ferment soluble fiber (gum) should be investigated. Their gastrointestinal tract anatomy suggests that they have a large capacity to harbor beneficial microbial populations, and their feeding ecology is heavily dependent on ingestion of plant gums to meet energy needs.
Limiting amino acids in captive sugar glider diets should be identified, and balance in commercial products should be adjusted to optimize protein nutrition.

Vitamin D metabolism should be examined in detail through controlled feeding studies.

Incidence and health implications of hemosiderosis should be surveyed in captive sugar glider populations.

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