Captive Marsupial Nutrition

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KEYWORDS

• Nutrition • Marsupial • Macropod • Sugar glider • Opossum • Wallaby

KEY POINTS

- Marsupials have a basal metabolic rate considered two-thirds of eutherian (placental) mammals.
- Diets for captive marsupials are based on what the animals eat in the wild.
- Diets for companion marsupials (sugar gliders, wallabies, Virginia opossums, and short-tailed opossums) have been developed.
- Hand-rearing marsupials requires using different formulations as the joey matures.

INTRODUCTION

Marsupials comprise an interesting group of mammals, which are increasingly being kept as pets (**Table 1**). These animals include the sugar glider (*Petaurus breviceps*), Bennett's wallaby (*Macropus rufogriseus*), tammar wallaby (*Macropus eugenii*), Virgina opossum (*Didelphis virginiana*), and the South American (Brazilian, Gray) short-tailed opossum (*Monodelphis domestica*). Few actual feeding trials have been published, although many anecdotal diets have years of usage with good success. Marsupials have dental and digestive tract adaptations that allow them to use specific niches in their environments. Wild-type diets have been extensively studied in sugar gliders and wallabies.[1–6] Wild-type diets have been observed for the Virginia opossum and the short-tailed opossum.[7–10] Knowing the diet in the wild is instrumental in designing diets used in captivity.

METABOLISM

Discussion of nutrition begins with metabolic rates, which relate energy and food requirements. There are 3 measures of the rate of metabolism: basal metabolic rate (BMR), field metabolic rate (FMR), and maximum sustained metabolic rate (MSMR). These 3 values are not available for all species of marsupials.

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Table 1
Summary of data on BMRs of selected marsupials

Species	Body Mass (g)	BMR			
		$mLO_2\ g^{-1}h^{-1}$[a]	$kJ\ kg^{-0.75}/d$[b]	$W\ kg^{-0.75}$[c]	%[d]
Didelphis virginiana	2403	0.380	238	2.71	81
Macropus eugenii	4878	0.283	212	2.42	72
Monodelphis domestica	104	0.608	161	1.83	55
Petaurus breviceps	128	0.692	209	2.38	71

[a] Mass-specific rate of metabolic intensity.
[b] Energetic equivalence of O_2 = 21 kJ L^{-1}.
[c] W = 87.72 kJ per day.
[d] Percentage of predicted value equation for eutherians. The "marsupial mean" is 70% of the eutherian.

Data from Hume ID. Metabolic rates and nutrient requirements. In: Marsupial nutrition. Cambridge (United Kingdom): Cambridge Press; 1999. p. 1–34.

- The definition of BMR of an endotherm is the minimum rate of metabolism compatible with endothermy. It is measured by the rate of oxygen consumption (heat production) of a nonreproductive, postabsorptive adult animal at rest (but not asleep) in its thermoneutral zone and not experiencing any physical or psychological stress.[11] In herbivores, a truly postabsorptive state is never fully reached without starving the animal because of the continued nature of digestive function, with constant production of nutrients by the host microbes.[11]
- FMR is the energy cost of free existence. It includes basal metabolism along with the costs of maintenance, thermoregulation, and activity.[11] Measurements of FMR often include other costs associated with growth, fat storage, and reproduction. Reproduction may include additional activity costs involved with defense of breeding territories, courtship, and foraging on behalf of young. FMRs are more variable for a species than BMR. Thus, FMR relates directly to the real world, and BMRs are more widely used for comparisons across species and taxons.[11]
- The MSMR is the highest rate of energy expenditure that an animal can sustain from food intake, without using body energy stores. It has been measured experimentally in small mammals by using combinations of physical activity, cold stress, and lactation.[11]

BMRs

The traditional view is that the BMR of marsupials is about 30% less than that of eutherian (placental) mammals.[10,11] A BMR for the "average marsupial" is considered to be 49 kcal or 204 kJ $kg^{-0.75}$ day^{-1} or 2.33 W $kg^{-0.75}$.[11] Variations in BMR among both marsupials and eutherians are strongly correlated with food habits, activity level, and precision of temperature regulation.[11]

CONSEQUENCES OF A LOW METABOLIC RATE

- One consequence of a low BMR is generally associated with a low body temperature. A low metabolic rate also has several important consequences for animals in terms of nutrient requirements and thus the width of their nutritional niche.[11]
- Other consequences in environmental tolerance and reproductive rate are related not only to an animal's BMR but also to its metabolic scope, which is the extent to which it can increase metabolism above basal to accommodate

high rates of heat loss in cold environments and the energetic costs of a high reproductive potential.

- A low BMR means lower food requirements for maintenance; energy reserves will last longer under adverse conditions.[11]

MAINTENANCE ENERGY REQUIREMENTS OF CAPTIVE MARSUPIALS

In captive wild animals and housed domestic stock, energy additional to basal requirements is needed for feeding, drinking, digestion, absorption, and metabolism of absorbed nutrients, and for postural changes, but little is needed for thermoregulation or other activities. Under these conditions, maintenance energy requirements are often approximately double the BMR. Metabolizable energy is converted to digestible energy using appropriate factors. With few exceptions, maintenance requirements are in the range of 150% to 250% of BMR. There also seems to be a trend for maintenance requirements as a multiple of BMR to decrease with increasing body mass of the species. This trend may reflect both a greater activity increment and greater requirements for thermoregulation in the smaller species, under captive conditions.[11]

FMRs

FMR, or the energy cost of free existence, is routinely measured by the use of doubly labeled water. The oxygen isotope traces both the water and the carbon dioxide in the body, so the difference between washout rates of oxygen and hydrogen is a measure of CO_2 production (metabolic rate). FMR has been measured in 28 species of marsupials (**Table 2** lists 2 species selected for this article).[11]

- FMR is more variable within a species than is the BMR. The main sources of variation can be identified from **Table 2** as being sex, season, and reproductive status.[11] Unlike BMR, a common scaling factor cannot be used to compare FMRs between the 2 therian groups. At a body size range of 240 to 550 g, FMRs of marsupials and eutherians are similar.
- At lower body sizes, FMRs of eutherians are lower. The only dietary comparison that can be made is within the herbivores, for which marsupials and eutherians both scaled to 0.64, which is the slope of the regression equation relating FMR to body mass. Herbivorous eutherians generally had higher FMRs than herbivorous marsupials, regardless of body size.[11]

More useful than FMR for comparative purposes is the ratio of FMR to BMR (calculated by dividing mass-specific FMR by mass-specific BMR). Analysis showed that the ratio decreased with increasing body mass in marsupials, but in eutherians, it increased with increasing body mass. The high ratio of FMR to BMR in small marsupials is consistent with their relatively high maintenance energy requirements in

Table 2
FMR of selected adult marsupials

				FMR			
Species	**Cohort**	**Season**	**Body Mass (g)**	**$mLCO_2\ g^{-1}\ h^{-1}$**	**kJ/d**	**kJ kg 0.58/d**	**FMR/BMR**
M eugenii	Adult	Summer	4380	0.518	1150	488	1.9
P breviceps	Female	Spring	112	2.563	153	545	3.9
	Male	Spring	135	2.671	192	613	4.1

Data from Hume ID. Metabolic rates and nutrient requirements. In: Marsupial nutrition. Cambridge (United Kingdom): Cambridge Press; 1999. p. 1–34.

captivity. Analysis of marsupial and eutherian FMR:BMRs showed that ratios were similar at large body size (5–8 kg). At small body size (10–20 g), the ratio in marsupials was twice that of eutherians.

METABOLIC SCOPE

The high FMR:BMR ratio of some small marsupial species raises the question of what is the highest rate of metabolism that can be sustained for the long term. Sustained metabolic rates are time-averaged rates of metabolism in free-ranging animals maintaining body mass over periods that are long enough so that metabolism is fueled by food intake rather than by depletion of energy reserves.

- Sustained metabolic rate is equivalent to the FMR of the animal in energy balance. They are less than peak, or burst metabolic rates, which are short term and fueled largely by anaerobic ATP production for energy stores (mainly glycogen).
- Peak metabolic rates are limited to no more than 1 or 2 minutes because of the toxic effects of lactic acid accumulation. During this time, there may be as much as a 100-fold increase in the animal's BMR. In contrast, aerobically fueled sustained metabolic rates are mostly between 2-fold and 5-fold BMR, but can be as low as 1.3 and as high as 7.2 in lactating ground squirrels, as an example.[11]
- These multiples of BMR are termed the animal's *sustained metabolic scope.*[11]

Metabolic rates higher than the MSMR of a species can be maintained over a shorter period in response to cold stress. These rates are fueled aerobically and the animal must maintain a stable body temperature. Such rates are called summit metabolic rates. The difference between summit metabolic rate and the species' BMR is its *metabolic scope*.[11]

- For example, the summit metabolic rate in the South American didelphid *M domestica* was 8 to 9 times BMR.
- Marsupials have lower metabolic rates than eutherians within their thermoneutral zone, but the same metabolic rates as eutherians below thermoneutrality.
- Marsupials and eutherians do not differ in maximal running speeds. These 2 lines of evidence indicate that the numerous consequences of a low BMR do not include restricted thermoregulatory or locomotory responses, and that marsupials have greater *metabolic scopes* than equivalent eutherians.[11]

TORPOR AND HIBERNATION IN MARSUPIALS

The very high rates of metabolism required for maintenance of endothermy in small mammals at low ambient temperatures are not sustainable unless food supply is constant in quality and quantity.

- In the absence of food, the internal energy stores deplete in a relatively short time, while normothermic. These small endotherms can save large amounts of energy by abandoning regulation of body temperature at their normal high levels.
- Heterothermy is particularly common in insectivores, both marsupial and eutherian, because a constant supply of insects is unlikely in the wild, and they cannot ameliorate fluctuations in food availability by caching food as granivores can.

Heterothermy is manifested in 2 related but distinct ways: shallow daily torpor and hibernation, which is a deep and prolonged torpor.

- The 2 states are distinct in terms of average maximum torpor duration (11 hours in daily torpor vs 355 hours in hibernation), mean minimum body temperature (17.4°C [63.3°F] vs 5.8°C [42.4°F]), minimum metabolic rate (0.54 vs 0.04 mL $O_2{}^{g-1}$ body mass^{h-1}), and minimum metabolic rate expressed as a percentage of BMR (30% in daily torpor vs 5% in hibernation).[11]
- Daily torpor occurs in South American didelphid opossums (eg, short-tailed opossum) and in Australian dasyurids and small possums from the family Petauridae (sugar glider and Leadbeater's possum).[11] These species are all omnivores that feed on a mixture of plant exudates and arthropods.[11]
- During torpor, body temperature, heart rate, respiration rate, and overall metabolism decrease; the same state may occur during anesthesia if care is not taken to maintain normal awake levels.
- If torpor is induced during anesthesia, it can complicate postoperative recovery (eg, hemorrhage can occur due to the increase in blood pressure that occurs as the body temperature and metabolism return to normal awake levels).[10]

OTHER NUTRIENTS

Relative to energy, water, and protein, there is only limited information on the requirements of marsupials for the micronutrients (vitamins, minerals, and essential fatty acids).

- There is no evidence of unusually high requirements for any micronutrient among marsupials, but there are suggestions that several micronutrients are required by some marsupials in extremely small amounts.[11]

SUMMARY OF METABOLISM POINTS

- The nutritional niche of a species can be defined principally by what it needs in terms of energy and specific nutrients, and how it harvests and extracts those needed nutrients from the food resources available.
- The amount of any particular nutrient required has 2 components: the amount needed for maintenance of the adult animals, and additional amounts needed for growth, reproduction, and free existence.
- Maintenance requirements are often closely related to the species' BMR, but the extent to which requirements are increased beyond maintenance in different physiologic states and by environmental factors depends on many factors.
- Knowledge of the basic biology and ecology of the species is necessary before the likely relative importance of these various physiologic and environmental factors can be appreciated. This knowledge applies particularly to the total energy and thus total food requirements of free-living animals.
- Information from captive animal studies under controlled conditions is vital for describing and understanding mechanism.
- Information from free-living animals in different season, different physiologic states, and different environments is equally vital for interpreting captive results and testing extrapolations from captivity to the wild state.
- Generally, marsupials have lower BMRs than their eutherian counterparts. They have lower maintenance requirements for energy, protein, and water, but at the level of FMRs marsupial-eutherian comparisons are limited by insufficient data.
- Summit metabolic rates of small marsupials are similar to those of small eutherians and thus small marsupials have greater metabolic scopes.

- Greater metabolic scopes in marsupials mean that a low BMR does not translate into limited capacity for thermoregulation or locomotory responses.
- In inadequate environments, a low BMR serves to maximize the life of energy stores.[11]
- Metabolism can be increased in response to high rates of heat loss or reproductive needs, allowing energy reserves to last longer in adverse conditions.[11]

DIETS IN CAPTIVITY

- The success of a diet designed for the captive marsupial depends on knowledge of the natural diet as well as nutrient needs and the digestive physiology.
- Relatively low requirements may also enable marsupials to use poorer quality diets of higher fiber content than analogous eutherians.
- Many marsupial herbivores feed on natural diets that are surprisingly high in fiber. This diet is possible because they have lower requirements for energy and nutrients when compared with their eutherian counterparts.
- There are dental adaptations for resisting or coping with abrasive plants, and a complex digestive tract in which microbial fermentation plays a central role in fiber degradation as well as the ability to recycle urea and degrade and resynthesize protein.
- In captivity, many marsupial herbivores are often fed concentrates that are higher in all facets of nutrition, frequently leading to obesity.[5]
- Improperly designed diets may also contribute to dietary-related disease. Appropriate diets and quantities must be stressed to owners.[10]

SUGAR GLIDER

Sugar gliders are omnivores with several specialized features that the captive diet should aim to use. They possess enlarged lower incisors for chewing into the bark of trees, lengthened fourth digit on the manus that may aid in the extraction of insects from crevices, and an enlarged cecum whose principal function is probably microbial fermentation of the complex associations of polysaccharides in gum (**Fig. 1**).[10,12–14]

- Observations of wild sugar gliders averaged over all seasons show that approximately 40% of foraging time is spent obtaining acacia gum, 30% is spent foraging for arthropods, and 11% is spent obtaining sap from eucalyptus trees (**Fig. 2**). Examination of feces and stomach contents, however, suggests that 49% of arthropods and 48% of gum are actually ingested.
- Manna, pollen, nectar, and honeydew are minor components of the natural diet in all seasons (**Figs. 3–5**).[12]
- **Table 3** has a description of these components. During autumn and winter, plant exudates predominate in their diet, but during spring and summer, they are primarily insectivorous. Moths, beetles, insect larvae, and spiders are preferred over exudates, possibly because of their increased demand for protein associated with breeding.[13]
- BMR measured in 128 g of captive sugar gliders is reported at 209 kJ $kg^{-0.75}$ per day or about 45 kJ per day (11 kcal per day).
- FMR has also been measured in sugar gliders at about 153 kJ per day (approximately 36 kcal) of a 112 g female glider and 192 kJ per day (approximately 46 kcal) for a 135 g male glider, about 4 times BMR.
- Normal captive activity energy requirements might thus be calculated at around 2 times BMR, or between 76.5 kJ and 96 kJ per day^{-1} (18–23 kcal) for animals

Fig. 1. Sugar glider showing the manus with lengthened fourth digit that aids in extraction of insects from crevices.

averaging approximately 124 g, although some studies suggest higher energy expenditures than this theoretic minimum.[15]

Field energetic studies have demonstrated that wild gliders consume 10.1 to 12.7 g/d of dry food, which provides 182 to 229 kJ/d. This amount is equivalent to approximately 9% of body weight in dry matter per day or about 17% of body weight in fresh food.

Fig. 2. Sap oozing from bites by sugar gliders.

Fig. 3. Manna.

- The captive glider expends less energy in exercise and is generally offered more assimilable foods than the wild glider, so the total energy offered in captivity should be less than or equal to this. Sugar gliders have a BMR similar to that of macropods.[12,13]

Fig. 4. Flowering eucalyptus as a source of pollen and nectar used by sugar gliders.

Fig. 5. Flowering Banksia sp. used by sugar gliders.

- The sugar glider has a low maintenance dietary nitrogen requirement of 87 mg $kg^{-0.75}$ per day due to an unusually low loss of metabolic fecal nitrogen (0.7 mg g^{-1} dry matter intake) compared with an average value in herbivorous marsupials of 2.8.[11]
- Endogenous urinary nitrogen (EUN) loss was also low in sugar gliders (25 mg $kg^{-0.75}$ per day) compared with an average value in macropods of 54. EUN is related more closely to the animal's metabolic rate than to any aspect of its protein metabolism.
- The explanation for the sugar gliders' low loss of nitrogen is that part of their endogenous nitrogen is retained by being recycled to the digestive tract. The gums on which it feeds are fermented in the cecum. Their high-energy diet may be expected to result in efficient trapping of recycled nitrogen, resulting in lower urea excretion rates than those of, for example, herbivores feeding on lower-energy plant material.[11,15]

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, or about 248 mg crude protein for a 100-g animal. Gliders displayed low nitrogen losses in both feces and urine, which may be related to low metabolic rates, overall, or to efficient use of potentially limited resource. Based on these laboratory studies, free-ranging male gliders are likely able to meet minimal protein requirements with diets

Table 3
Definition and composition of dietary components of wild sugar gliders

Component	Definition	Composition
Gum	Exuded on trunks and branches by some species of Acacia to bind sites of damage, particularly those made by insects	Complex associations of polysaccharides (cellulose, starch, and sugars), low in protein (1.3%–3.1%)
Arthropods	Moths, beetles, caterpillars, weevils, and spiders	Vary in composition but contain in the region of 50%–75% protein, and 5%–20% fat on a dry weight basis
Sap	Liquid obtained by biting through the bark of some eucalyptus trees into the phloem	1.4% or less protein, predominantly carbohydrate, of which 70%–85% is sucrose
Manna	Sugary exudates produced at sites of insect damage on the leaves and branches of certain eucalyptus and angophoras	Composition of sugars slightly changed from phloem sap by the action of insects' salivary enzymes
Honeydew	Sap-sucking insects ingest large quantities of sap to obtain sufficient protein and then excrete surplus carbohydrates as honeydew	About 79% monosaccharides and oligosaccharides and 9% polysaccharides
Nectar	Produced in usable quantities by larger eucalyptus flowers (>5 mm in diameter)	Many simple sugars

Data from Booth RJ. General husbandry and medical care of sugar gliders. In: Bonagura JD, editor. Kirk's current veterinary therapy XIII. Philadelphia: WB Saunders; 2000. p. 1157–63.

comprising exudates alone, but female gliders must supplement with pollen or arthropods to meet demands of reproduction.[11]

A recent feeding trial comparing 3 diets in young, growing male gliders averaging 96 g found animals consumed 100.1 kJ to 147 kJ (24–35 kcal) per day.[15] Sugar gliders do not hibernate but can display shallow daily torpor periods, with a drop in body temperature from about 35°C (95°F), to 11°C (51.8°F), to 28°C (82.4°F) for several hours, accompanied by decreases in metabolic rate to 10% to 60% of basal metabolism, mainly in response to food restriction.[15]

The suitability of the captive diet can be judged by monitoring body weight, body condition, coat condition, and fecal consistency.

- Despite the current detailed knowledge and the fact that gliders have been kept as pets for several years, many still present for veterinary care with problems related to improper feeding, including malnutrition, osteodystrophy, and dental disease.[15,16]
- Obesity is a common problem in captivity. Captive animals are often fed an excess quantity of food, excess simple sugars, and excess fat, combined with insufficient exercise.
- The captive diet should include nectar, insects, and other protein sources as well as limited amounts of fruits and vegetables. The quantity of food provided should be limited to 15% to 20% of body weight, depending on energy requirements associated with age, ambient temperature, breeding condition, and enclosure size.[17]
- Body weight should be monitored regularly and the quantity fed adjusted accordingly.

- Body condition can be assessed by palpation of the gliding membrane, which should be thin and flexible, not rounded with fat. Normal feces are elongated, firm ellipses 12 mm $\times$ 4 mm and dark-brown to black, and are sometimes joined by hairs ingested when the animal grooms.[12]
- The diet should be offered in fresh portions in the evening.

In groups, some individuals may emerge early to consume more than their share of food. Multiple feedings stations in the enclosure should be provided, or obese, dominant animals can be locked in the nest box until subordinate animals have fed.

- A portion of the diet should consist of sources of fruit sugars, preferably in the form of a sap or nectar. Sources include fresh nectar, maple syrup, honey, and artificial nectar products.
- Examples of commercial products include prepared lory diets and Gliderade (Avico, Fallbrook, CA).
- Gum Arabic (acacia) can be purchased as a powder, mixed into a thick paste, and used to simulate native gums: it can be used in holes in branches and on surfaces, with insects or bits of fruit stuck to it for enrichment and foraging.[13] Discussion of gum acacia is similar to the Australian acacia sp. Gum acacia has been shown to contain 1% dry weight calcium (Ca) and offsets the lack of Ca in arthropods eaten by the Senegal bush baby. In this respect, it would be valuable to know if mineral content of gums is similar between African and Australian acacia, such that gum Arabic might provide a suitable, available substitute feed for gliders.[15]
- Various commercial diets for sugar gliders and insectivores are available and may be included as a part of the diet.
- Leafy green vegetables provide a source of fiber and some vitamins. Sugar gliders accept a wide variety of other foods, including fruits, vegetables, nuts, and seeds (sunflower, pumpkin), but these should be offered in very limited quantities.
- Fruit juices and strained baby foods can be offered if they are free of preservatives, but they are not as appropriate as the nectar-based formulas. Because these foods are not a significant component of the natural diet, they should constitute less than 10% of the captive diet.
- Sprinkle a broad-spectrum vitamin and mineral supplement with a good Ca supply on the food daily.[9,13,18]

Contrary to nutritional needs observed in the wild, much of the information found in lay publications lists fruits and vegetables as a major portion of the captive diet.

- Fruit-based diets are harmful to captive sugar gliders because they provide inadequate protein and Ca and predispose animals to osteoporosis and periodontal disease.
- Although sugar gliders readily accept fruits, nuts, and grains, these are not a substantial part of their natural diet.

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 comprising unsupplemented animal products, such as meat, eggs, and insects.[15]

Leadbeater's diet has been recommended as a base mixture for many sugar glider diets. This diet is an artificial nectar mix originally formulated for Leadbeater's possums (*Gymnobelideus leadbeati*). Leadbeater's recipe is listed in **Box 1**.

- The mixture is kept refrigerated until served, with the unused refrigerated portion discarded after 2 to 3 days. The mixture can be kept longer if frozen.
- The original Leadbeater's recipe is often modified by individuals with adjustments usually being made for palatability rather than nutritional content. Several modified versions are found on the Internet, such as Bourbon's Modified Leadbeater's Diet and the High Protein Wombaroo Diet (Wombaroo, Adelaide, SA, Australia). These diets should be scrutinized closely because they have not undergone thorough nutritional dietary trials and analysis.

A detailed study to investigate basic nutritional parameters was conducted comparing 3 commonly fed captive diets in sugar gliders.[16]

The following 3 diets were tried:

- Diet A: 15 g insectivore fare (Reliable Protein Products, Phoenix, AZ);
- Diet B: 15 g soaked dry test extrusion (the dry extrusion was soaked in water to improve palatability as a ratio of 1 part dry kibble [Eight in One Pet Products, Hauppauge, NY] to 2 parts water); or
- Diet C: 15 g homemade formulation, Bourbon's Modified Leadbeater's diet (for the most current version of this recipe description, see http://www.sugargliders.org/gliderinfo/diets/bml.htm). Fifteen grams of frozen mixed vegetables (peas, corn, and carrots) and assorted fresh fruit or frozen berries were offered with each treatment.
- Diet A was supplemented daily with 1 g of a 1:1 mix of RepCal Ca supplement (nonphosphorus with vitamin D_3; Rep-Cal Research Labs, Los Gatos, CA) and Vionate powder (Gimborn Pet Specialties, LLC, Atlanta, GA) added to the fruit. In addition, diet A contained 4 protein supplements each week. One teaspoon 1:1 of chopped boiled chicken and Special K (Kellogg's, Battle Creek, MI) cereal mix moistened with apple juice was added on 2 days and 10 mealworms were added on 2 other days.
- Diet B was supplemented daily with 0.5 g of Frugivore Salad Supplement (HMS Diets, Bluffton, IN) on the produce mixture, and 5 mealworms were added 4 times a week.
- Diet C was supplemented with 5 mealworms added 4 times a week. As for the basal diet, the soaked kibble diet (diet B) appeared to be consumed to the greatest extent, followed by diet C, and last, insectivore fare. Vegetables were the least preferred. The analysis of the chemical composition of diets offered to and eaten by sugar gliders is shown in **Table 4**.

The conclusion of the authors was that none of the 3 diets tested appear to contain the optimal balance for meeting the nutritional needs of sugar gliders, but the information obtained did provide further insight into the dietary requirements.

- Ca deficiencies can lead to tetany and have been reported in gliders. These deficiencies have been linked with diets high in fruits and insects, preferred food items that can be poor sources of Ca, and hence, the need for supplementing this mineral. However, one must be careful in supplying Ca to maintain nutrient balance. The optimal ratio of Ca and phosphorus (P) is 1:1 to 2:1, at least as much Ca as P and, optimally, twice as much Ca as P.
- In these diets, only diet B (soaked kibble diet) contained the optimal Ca:P ratio, and it was marginally optimal at 1:1.

Box 1
Diets suggested for sugar gliders

1. 50:50 Leadbeater's mixture: insectivore diet (Reliable Protein Products, Mazuri; see Table 7) Leadbeater's:
   - 150 mL warm water, 150 mL honey, 1 shelled hard-cooked egg, 25 g baby cereal, 1 teaspoon vitamin/mineral supplement. Mix warm water and honey. In a separate container, blend egg until homogenized, gradually adding honey/water, then vitamin powder, then baby cereal, blending thoroughly after each addition until smooth. Keep refrigerated until served.
2. Chicago Zoo:

   1 teaspoon-sized piece each, chopped: apple, carrot, sweet potato, banana, leaf lettuce, $^1/_2$ hard-cooked egg yolk, 1 tablespoon Nebraska Feline diet (or other good-quality zoo feline diet such as Mazuri; see Table 7), 1 dozen mealworms.
3. Taronga Zoo (feeds 2 gliders):

   3 g apple, 3 g banana/corn, 1.5 g dog kibble, 1 teaspoon fly pupae (mealworms substituted here), 3 g grapes/kiwi fruit, 2 teaspoons Leadbeater's mix, 4 g orange with skin, 2 g pear, 2 g cantaloupe/melon/papaya, 3 g sweet potato. On Wednesdays: feed day-old chick large insects (crickets substituted here), when available.
4. Booth diet:

   Offer a total of 15%–20% of body weight daily. Select one diet (a or b) from each of the following groups (1, 2, and 3) every day. Rotation between the diets is recommended but not necessary. Animals will benefit from a regular supply of vitamin/mineral-enriched insects.

   Group 1

   a. Insects: 75% moths, crickets, beetles; 25% fly pupae, mealworms

   b. Meat mix: commercial small carnivore or insectivore mix

   Group 2

   a. Nectar mix: 337.5 g fructose, 337.5 g sucrose (brown sugar), 112.5 g glucose made up to 2 L with warm water; commercially available mixes have some vitamin/mineral additives and may be used.

   b. Dry lorikeet mix: 900 g rolled oats, 225 g wheat germ, 225 g brown sugar, 112.5 g glucose, 112.5 g raisins or sultanas

   Group 3

   a. Fruit and vegetables: select for diced apple, nectarine, melon, grapes, raisins, sultanas, figs, tomato, sweet corn kernels, sweet potato, beans, shredded carrot, butternut pumpkin

   b. Greens: mixed sprouts, leaf/romaine lettuce, broccoli, parsley; with a vitamin/mineral supplement at the manufacturer's directions
5. Dierenfeld Diet 1: an adequate sample daily diet:

   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 vertebrates, such as grasshoppers, moths, fly pupae, crickets, optional)

   Such a diet provides 126 kJ energy, 21% crude protein (1750 mg), 0.77% Ca, 0.64% P, vitamin D 1.1 IU/g with this particular dry (generic) cat food
6. Dierenfeld Diet 2: blend into a slurry:

   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 (1550 mg), 0.61% Ca, 0.44% P, and vitamin D 0.9 IU/kg.

Data from Refs.[10,12,13,15,16,18]

Table 4
Chemical composition (nutrients on a dry matter basis) of diets offered to and eaten by sugar gliders, n = 3 animals per treatment

Diet	% Protein	% Fat	% Ca	% P
Diet A: Offered	25.6	6.6	1.3	0.2
Eaten	23.5	5.6	2.0	0.2
Diet B: Offered	25.9	13.8	0.7	0.7
Eaten	25.6	13.5	0.7	0.7
Diet C: Offered	18.6	7.6	2.9	0.4
Eaten	19.0	8.8	3.5	0.5

- Diet A, as prepared, contained 6.5 times more Ca than P, and as eaten, 10 times more Ca than P.
- Similarly, diet C contained 7 to 8 times more Ca than P. Although absolute Ca requirements of sugar gliders are unknown, based on other animals, a value between 0.5% and 1% of dry matter is anticipated for this species, with a dietary P requirement between 0.2% and 0.5%.
- Diet B appears too high in P relative to Ca, whereas diets A and C both appear too low.
- Bone density checks through radiographic examination would be one means of evaluating whether these diets may have affected bone quality though imbalanced Ca:P ratios. Radiographs appeared normal in all gliders during the course of this investigation.[16]

They did find the following:

1. Young, healthy male gliders appear to require between 105 kJ per day and 147 kJ per day—not many calories.
2. Total protein (as nitrogen) was apparently not limiting in any of the diets, but quality may have been marginal, particularly in diet C (evidenced by weight loss).
3. Diets currently being fed to captive sugar gliders are highly digestible; however, additional comparisons to determine digestibility of natural diets, especially gums, to target optimal nutrient levels are required; and
4. Evidence of mineral and vitamin imbalances in commonly fed diets, especially vitamin D and iron, which may be impacting health, need to be investigated further.
   - One discussion item was also needed to identify whether gliders have the enzyme for making their own vitamin C as do many animals. If so, excess dietary supplementation may not be warranted and may actually contribute to iron overload.
   - Still also needing investigation is blood carrier and storage proteins for iron saturation of transferring and ferritin in this species.
   - Still needed to know are the effects of gums on the gut health. They have a huge cecum for fermenting soluble fiber and really are not given much opportunity to do so with current feeding practices. The effects of different, simple and complex sugars on gut health, microbiology, and overall physiology need to be investigated in more detail.[16]

FEEDING RECOMMENDATIONS

- Adult captive sugar gliders weighing 130 g require between approximately 76 kJ and 147 kJ (18–35 kcal) per day to meet maintenance energy requirements, containing less than 500 mg crude protein, depending on protein quality.[15,16]

- 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.
- As a broad rule of thumb, a mixture of one part dry or semi-moist commercial product to 2 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), then 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.

Box 1 lists several diets that have been fed successfully to sugar gliders. A diet should be chosen and fed in its entirety. The diet should be offered in fresh portions in the evening. Commercially available adult insects should be fed a Ca-rich insect diet for several days before being offered. Larval forms should be kept to a minimum. Chop the pieces together so that the gliders cannot pick out only their favorite items. No commercial diets seem totally adequate, but long-term nutritional studies are still pending.

- 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 vegetables should not be used.
- Fresh produce is preferred, particularly fruits and vegetables that contain more Ca than P (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).
- Treats 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.[15]

MACROPODS

Macropods are herbivorous foregut fermenters with a chambered stomach.

- The stomach comprises a sacciform forestomach, tubiform forestomach, hindstomach, and pylorus. Microbial fermentation of ingested material occurs in the enlarged forestomach, with hydrochloric acid and pepsinogen being secreted in the hind stomach.
- A cecum is present but is not considered a major site of fermentation.[14]
- Merycism occurs in some macropods and is defined as regurgitation and reingestion (but no remastication) of forestomach contents. The kangaroo releases virtually no methane gas during eructation and exhalation due to the hydrogen byproduct of fermentation being converted into acetate, which is used for additional energy.

- The major advantages of foregut fermentation are the degradation of plant toxins and the ability to extract nutrition for poor-quality forage.
- Detailed physiologic and anatomic studies suggest that the macropod forestomach has more in common with the equine colon than the bovine forestomach.[2,14,19]

Macropods can be loosely grouped into 3 main classifications based on dietary preference:

1. Primary browsers
2. Primary grazers
3. Intermediate browser/grazer grade.
   - In general, the larger species tend to be primarily grazers, whereas the smaller species are primarily browsers. The Tammar and Bennett's wallabies are classified as intermediate grades, with wild-type diet being short grass, forbs, and bushes. The red kangaroo (*Macropus rufus*) is an example of a grazer (grass, forbs).[19]

ENERGY METABOLISM

On average, marsupials have a lower metabolism rate than their eutherian counterparts.

- The BMR of most marsupials decreases between 65% and 74% (mean, 70%) of the calculated BMR for a eutherian mammal of equal weight, with macropods ranging from 57% to 88%.
- This lower BMR results in lower average body temperatures and an overall decreased caloric requirement when compared with eutherians.
- The maintenance energy requirement for marsupials is usually 150% to 250% of the BMR, with larger marsupials having a maintenance energy requirement in the lower end of the range.[2,19]

The primary source of energy for macropods is short-chain fatty acids produced by microbes through fermentation.

- Most short-chain fatty acids are produced and absorbed in the forestomach, with production and absorption highest in the sacciform region.
- The cecum and proximal colon also serve as a secondary site of microbial fermentation.
- Short-chain fatty acids can lower the forestomach pH from approximately 8.0 in a fasting animal to approximately 5.0 in a recently fed animal.
- The types and proportions of short-chain fatty acids are similar to those produced in the rumen of domestic species.
- Like in ruminants, large proportions of acetic acid are converted to butyric acid, the principal short-chain fatty acids used by the forestomach epithelium for energy.
- Byproducts of this reaction are ketone bodies, especially acetoacetate, which can be further oxidized by other tissues.
- Unlike ruminants, however, in which this ketogenic activity occurs throughout the squamous epithelial lining of the rumen, ketogenic activity in macropods is restricted to the cardiac glandular mucosa.[2,20]

Microbial fermentation also results in production of ammonia, which serves as the primary nitrogen source for microbial protein synthesis.

- The ability of microbes to break down proteins, other microbes, and nonprotein nitrogen sources into ammonia allows macropods to use different nitrogen sources of varying quality. During periods of nitrogen shortage when ingesting a low-protein diet, macropods are able to recycle endogenously produced urea into the gut to be used as a nitrogen source instead of excreting it in the urine. Gases produced by forestomach fermentation are primarily carbon dioxide and hydrogen. Methane is also produced, especially during active eating, but at lower levels compared with ruminants.[2,20]
- Soluble sugars are rapidly digested and absorbed in the sacciform forestomach. This process results in little disaccharidase activity in the small intestines, because few digestible carbohydrates ever reach this location before they are broken down by microbes and absorbed.
- Similar to sheep, there is minimal glucose uptake into the liver. Instead, the liver continuously produces and releases glucose into the blood through gluconeogenesis, which occurs postprandially and during fasting.
- Macropods exhibit considerable tolerance to hypoglycemia induced by intravenous injections of insulin; however, they are much less tolerant of hyperglycemia.[2,19,20]

The tubular flow of ingesta through the macropod forestomach results in a shorter retention time.

- One disadvantage to this system is that digestibility of the ingesta is lower compared with ruminants of similar size.
- An advantage of this system is that dietary fiber continues to move through the forestomach regardless of fiber length and size.
- In ruminants, the rumen retains fiber particles until they are degraded to a certain size, which prolongs digestion and results in greater rumen fill and decreased dietary intake. High-fiber diets can limit food intake in ruminants.
- Dietary intake in macropods depends less on fiber content. Smaller macropods (with larger sacciform forestomachs) are more affected by dietary fiber than the larger grazing macropods.[19]

In captivity, macropods should be given a diet that best approximates the forage consumed by wild members of a given species. Access to high-quality grass pasture is recommended, especially for grazing species (**Fig. 6**). Nontoxic browse items also can be offered to provide variety and mimic natural behaviors. For many species, providing fresh limbs with leaves and bark allows macropods to consume the leaves

Fig. 6. Macropods should be provided good quality fresh hay.

and strip the bark, which also provides behavioral enrichment. An example of diet composition is listed in **Table 5**. **Table 6** lists micronutrient composition needed by macropods.[19]

Basic captive diets mimic those fed to ungulates.

- Items are given in lower quantities on a per weight basis, however, because of lower metabolism rates of macropods.
- If overfed, some species (especially smaller ones) are predisposed to obesity.
- Good quality grass hay is recommended ad libitum for all species, especially if not kept on a grass pasture.
- Quality is important because coarse, sharp, or abrasive food items (eg, oat awns, stalky hay, hay contaminated with thorny plants) can cause oral trauma and provide an avenue for secondary bacterial infections that lead to soft tissue infections, dental lesions, and osteomyelitis (commonly but controversially referred to as "lumpy jaw"). Lucerne (alfalfa) can also be offered.
- Food items should not be too soft either (eg, bread), because soft foods do not adequately toughen the oral mucosa or wear the teeth to allow molar progression.
- Macropods are susceptible to toxoplasmosis from ingesting food items contaminated with infected cat feces.
- Contamination of hay from barn cats at the hay storage location has been implicated as the source of toxoplasmosis outbreaks in several zoologic collections.
- It is recommended that food items be fed elevated from the ground (eg, in a hay rack, elevated bowl, or trough feeder) to prevent contamination with feces and reduce the transmission of parasites. Food containers should be cleaned daily and regularly disinfected.
- To reduce food competition and aggression, multiple feeding areas are recommended when macropods are kept in a group.[21]

Box 2 lists a suggested diet for captive macropods. Pelleted rations are also recommended in moderation. Several commercially available pellets formulated specifically for macropods are available and are listed in **Table 7**.

- Vegetables can be offered in small amounts, and fruits can be used only as an occasional treat. These produce items must be restricted to a small proportion

Table 5
Macropod pelleted diet example: pelleted maintenance diet for grazing kangaroos

Component	Inclusion (% of Air-Dried Feed)
Milled straw	50.0
Chopped alfalfa (Lucerne) hay	47.0
NaCl	0.75
CaH_2PO_4	0.75
$CaCO_3$	0.75
$MgSO_4$	0.12
KCl	0.22
$NaSO_3$	0.21
Micronutrient mix	0.20

Data from Hume ID, Barboza PS. Designing artificial diets for captive marsupials. In: Fowler ME, editor. Zoo and wild animal medicine. 3rd edition. Philadelphia: WB Saunders; 1993. p. 281–8.

Table 6
Micronutrient mix for grazing marsupials

Component	Amount (/kg of Air-Dried Feed)
Fe	10 mg
Co	1 mg
Mn	58 mg
Zn	50 mg
I	0.7 mg
Se	2 ng
Vitamin A	12,000 IU
Vitamin D	2400 IU
Vitamin E	30 IU
Vitamin B1	2 mg
Vitamin B2	6 mg
Vitamin B6	2 mg
Vitamin B12	20 ng
Pantothenic acid	5.5 mg
Niacin	26 mg
Choline	200 mg
Vitamin K	0.6 mg
Biotin	320 ng
Folic acid	0.4 mg

of the diet, however, because they contain higher levels of simple sugars and carbohydrates and are easily fermentable, possibly leading to gastrointestinal and dental problems.

- Sweet feed mixes should not be used for the same reasons.
- Items such as bread, peanut butter, jam, and other sweet treats may be helpful in getting a macropod to take medications, but they should not be a regular part of the diet (Fig. 7).

Box 2
Suggested diet for macropods

- Free-choice grass or Timothy hay or pasture for grazing
- Daily concentrate herbivore pellet to provide energy, microminerals and macrominerals, with vitamin E
- Pelleted feed approximately 25% daily diet
- Complete marsupial feeds, such as Mazuri Kangaroo Pellet (PMI Nutrition International, Inc, Brentwood, MO)
- Nonmarsupial herbivore pelleted feed (Mazuri Lagomorph, Equid, Oxbow Rabbit), must be supplemented with Vitamin E at 200–600 mg/d for adult macropods.
- Treats: small amounts of domestic produce (vegetables, occasional fruit). Domestic produce is high in carbohydrates and generally low in fiber.

Data from Refs.[9,10,17]

Table 7
Guaranteed analysis of selected commercial diets

Diet	Protein %	Fat %	Fiber %	Form	Product Size
5Z88 Mazuri Exotic canine diet	28.5	18.0	4.0	Extruded particle	3/8″ × 5/16″
5661 Mazuri Equid maintenance	13.0	2.0	15.0	Pellet	5/32″ × ½″
5MK8 Mazuri Insectivore diet	28.0	12.0	13.0	Extruded particle	1/16″ × 1/16″
5Z88 Mazuri Kangaroo/wallaby	15.0	5.0	10.0	Extruded pellets	3/8″ × 3/16″
5652 Mazuri Lagomorph diet	16.0	2.0	18.0	Pellet	5/32″ × ¾″
5635 Mazuri Omnivore zoo feed "A"	25.0	6.0	5.0	Extruded biscuit	½″ × 1″
Fox reproduction diet, Milk Specialties Company	35.0	13.0	4.5	Extruded pellet	1/4″ diameter
Insectivore fare, Reliable Protein Products	20.0	6.0	6.0	Soft pellets	1/4″ diameter
Oxbow Pet Products Essentials Adult Rabbit	14.0	2.0	25–29	Pellet	¼″ × ½″ approximately

Data from Refs.[22–24]

- Carrots can be offered as treats.
- Salt blocks are recommended for the species commonly kept in captivity as a source of electrolytes and minerals.
- Fresh, clean water should be offered daily to all macropods. Although some species are drought-tolerant, captive diets usually contain less moisture than wild forages, which increases the captive animal's need for water intake. Plants toxic to domestic herbivores or chemically treated items should not be fed.[19,21]

Vitamin E is an antioxidant required by macropods to prevent myopathy, or white muscle disease.

Fig. 7. Kangaroos clutching bagels for photograph. Such food item is not recommended.

- Hind limb weakness that progressed to paralysis, muscle wasting, and death was described in captive Quokkas (*Setonix brachyurus*) fed a commercial sheep pellet.
- Smaller enclosure sizes were found to increase the requirement of vitamin E because of the additional stress of overcrowding.
- Myopathy, however, was prevented with vitamin E supplementation regardless of enclosure size.
- In most species of animals, selenium can be used as an antioxidant substitute in place of vitamin E to prevent myopathy, but selenium supplementation alone was found to be ineffective in preventing myopathy Tammar wallabies.
- Vitamin E supplementation is recommended for all macropods. The amount required will vary based on the vitamin E content of the diet ingredients. Feeding large amounts of varied natural browse may reduce the need for vitamin E supplementation.[19]

Table 7 lists commercial diets mentioned in this article.[22–24]

VIRGINIA OPOSSUM

Virginia opossums are true omnivores.[10,17,25]

- The diet eaten by free-ranging opossums includes any and all green and yellow vegetables, grass, fruit, carrion, snails, slugs, worms, insects including flies, earwigs, roaches, amphibians, eggs, crayfish, and fish.[10,25,26]
- They may also eat birds but rarely eat the entire carcass.
- In captivity, they can be fed a varied diet that includes good-quality dog and/or cat foods, various vegetables, fruits, an occasional egg, supplemental Ca and vitamin A, live foods (such as crickets, slugs, mealworms), and yogurt. Opossums are particularly indiscriminate and will consume nearly any food offered.[17] Formulations have been developed for different stages of life.
- The gastrointestinal morphology is consistent with that of many other mammalian omnivores.
- The dental formula is 5/4, 1/1, 3/3, 4/4.
- The salivary glands include large mandibular and smaller parotid and sublingual glands.
- The distal esophagus has raised, transverse rugae and comprises smooth muscle fibers.
- The opossum's distal esophagus, pylorus, and ileocecal junction have been studied extensively, because the smooth muscle arrangements in these areas closely resemble that of humans.[27]
- Virginia opossums have a simple, globular stomach; most of the gastric mucosa is composed of fundic glands.
- Pyloric glands, and a narrow ridge of cardiac glands, exist near the esophageal-gastric border.
- Like most placental mammals, opossums have enteroendocrine cells lining portions of the gastrointestinal tract. These cells, in addition to endocrine cells in the pancreas, aid in secreting peptides that control various digestive functions, such as gastric acid secretion, pancreatic secretion of electrolytes and enzymes, and contraction of the gall bladder.
- In the stomach, 90% of the enteroendocrine cells are located in the pyloric region and secrete a variety of hormones, such as gastrin, gastric-inhibitory peptide, secretin, cholecystokinin, and pancreozymin.[27]

- The Brunner's glands secrete their products into mucosal depression located on the duodenal wall.
- The cecum is simple, conical, and approximately 20% to 40% of the total body length.
- Distal to the cecum, the colon is mobile because of its simple, loose mesenteric attachment.

ADULT OPOSSUM NUTRITION

In a study of opossums in New York, analysis of the stomach contents of 187 road-killed opossums showed that the average opossum diet consisted of 18% fruit, 17.2% amphibians, 14.2% mammals, 13.4% insects, 6.6% grass, 5.4% worms, 5.3% reptiles, 5% birds, 4.8% carrion, and 6.7% other items. Another study showed that stomach contents of road-killed opossums in Portland, Oregon consisted of 27% mammals, 11% leaf litter, 10% fruits, seeds, and bulbs, 10% gastropods, 9% garbage, 9% earthworms, 9% pet food, 8% grass and green leaves, 3% insects, 3% birds, and 1% unidentified animal tissue. Both studies looked at stomach rather than fecal content because fecal analysis reveals food items that readily pass through the gastrointestinal system and may not account for more digestible food items.[27]

Many adult diet variations exist. Maintaining the proper Ca:P ratio and avoiding high fat meals should be a priority.

- Virginia opossums need an increased Ca component in their diet, especially as juveniles and young adults, that is typically consumed as whole prey and egg-shells. As these items are usually minimized in captive rations, a human pediatric Ca supplement should be offered daily until full maturity.
- Milk products should be fed scarcely, as they are lactose-based; this sugar is poorly tolerated by the marsupial digestive system.[17]

Suggested diets for adult opossums are listed in **Table 8**.

VITAMINS

- If given an appropriately balanced diet, healthy opossums do not need vitamin supplementation.
- When appropriate diets are given, vitamin deficiencies are uncommon, and the risk of health problems associated with over-supplementation can be avoided.
- Vitamin D deficiencies are uncommon in opossums because they, like other crepuscular mammals, are highly efficient at producing vitamin D_3 (cholecalciferol, the active form of vitamin D) in the skin, compared with diurnal mammals that require exposure to sunlight to active vitamin D. If vitamin D must be supplemented, only products that contain cholecalciferol should be given. Over-supplementation with vitamin D can lead to demineralization of bone and mineralization of soft tissues and should be avoided. A single dose of vitamin D_3 may be stored in the body for as long as 6 months.[27]

Opossums usually do not need to be supplemented with vitamin A, which is fat soluble and derived from carotenoids found in plants.

- It is formed in the intestinal epithelium of most animals and stored in the liver. Vitamin A is essential for maintenance and growth of surface epithelium, eye pigmentation, and bones.
- Over-supplementation can prevent bone formation and stimulate bone resorption.

Table 8
Suggested diets for adult opossums (choose one and use in entirety)

Diet 1	Diet 2	Diet 3
Evening: 112.5 g chopped mixed vegetables (not corn, peas) 15 g mixed chopped fruits (not citrus) 15 mL nonfat yogurt 56 g insectivore or omnivore zoo pelleted diet 3–4 times a week: 0.25 hard-cooked egg OR 15 g canned salmon OR 56 g cooked tofu 50 mg pharmaceutical grade calcium carbonate or Ca gluconate powder: mix into the vegetables/fruit at least 3 times a week Children's multiple vitamin can be given 1–2 times a week as a treat Other treats: 1 king mealworm OR 1–2 Ca gut-loaded crickets OR 3–4 mealworms: 2–4 times a week Morning: 56 g dry cat food, insectivore, omnivore kibble	Evening: 56 g dry dog food, insectivore, or omnivore kibble 56 g meat-based canned dog or cat food mixed into the kibble 56 g mixed fruit 56 g mixed vegetables Calcium carbonate should be sprinkled on fruits/vegetables and mixed in Morning: 56 g dry cat, insectivore, or omnivore kibble Treats: Once daily 5 mL nonfat fruit yogurt OR 1 children's multiple vitamin OR 1 king mealworm OR 1–2 Ca-loaded crickets OR 3–4 mealworms	6 tablespoons of a dry, high-quality cat food $\frac{1}{2}$ cup of small vegetable chunks 2–3 teaspoons of fruit 7 tablespoons of a high-quality canned dog food Several earthworms 1 hard-cooked egg with shell 1 whole mouse (approximately 30 g) Feed once a day; unlimited fresh water

Data from Refs.[10,25,27]

- Supplemental vitamin A should be given only when deficiencies are suspected, and doses should be carefully monitored, because hypervitaminosis A can contribute to metabolic bone disease.[27]

The most common nutritional diseases seen in pet Virginia opossums are nutritional secondary hyperparathyroidism caused by Ca:P imbalances or deficiency of Ca, obesity, and dental disease.[25]

Food consumption required is about 150 to 200 g per day per adult. To prevent obesity, dry food may need to be limited and fed as meals rather than ad libitum. Commercial dry hedgehog/insectivore diet is being used in place of dry dog/cat food. No feeding trials have been done, but the commercial insectivore and omnivore diets are generally lower in fat than the dog/cat foods, which may be advantageous for controlling weight.[10] Suggested diets are listed in **Table 8** (**Fig. 8**).

Fig. 8. Adult opossum with diet showing insectivore pellets and chopped vegetables.

SHORT-TAILED OPOSSUM

Wild short-tailed opossums eat small prey (mice, insects), fruit, grains, and carrion.[9]

As laboratory animals, they have been maintained and bred with success using a commercial pelleted fox food (Reproduction Diet, Nutritionally Complete Fox Food Pellets; Milk Specialties Products, New Holstein, WI).[9] It has a fat content of 10% dry weight and cholesterol content of 0.15% of dry weight. Opossums fed a diet containing 18.8% fat with cholesterol content of 0.71% in genetically predisposed animals developed hypercholesterolemia.[28,29] They are used as an animal model of dietary-induced hyperlipidemia and hypercholesterolemia. They have also been successfully maintained in the laboratory on a diet of Purina Cat Chow (Nestle Purina, St Louis, MO) fed ad libitum.[30] Supplements have been insects and pinky mice. Usually the meal is fed in the evening. Live foods are let loose in the cage. Fruit can be placed on branches to encourage foraging and exercise (Fig. 9).[10] Suggested diets for the short-tailed opossum are listed in Table 9.

Fig. 9. Short-tailed opossum with grapes placed on branches for foraging.

Table 9
Suggested diets for the short-tailed opossum

Diet 1 (Adapted from the National Zoo, Washington, DC)	Diet 2
5 g of blended meat mixture comprising:	5 g commercial insectivore diet (hedgehog dry kibble, zoo insectivore pellet diets)
225 g chopped, cooked lean meat (horse or beef)	2.5 g cooked meat (turkey, chicken, beef, deboned fish) sprinkled with powdered multivitamin/mineral supplement
1 hard-cooked egg	1-cm cube of fresh fruit (kiwi, orange, apple, grape, banana) sprinkled with powdered multivitamin/mineral supplement
15 g wheat germ flakes	1 or 2 Ca gut-loaded crickets
10 g powdered milk	1 large mealworm and 6 small mealworms OR 2 large mealworms OR 10 small mealworms. Note: adult insects are more nutritious than larval forms.
2.5 g powdered multivitamin/mineral supplement	In addition, 3–5 times a week:
This mixture is supplemented daily with:	1.25 g hard-cooked egg (chop white and yolk together, sprinkle with vitamin/mineral supplement)
1-cm cube of fresh fruit (kiwi, orange, apple, grape, banana)	1.25 g cottage cheese or skim-milk cheese
1-cm cube of commercial marmoset diet	
1 or 2 Ca gut-loaded crickets, 6 small mealworms OR 2 king mealworms OR 10 small mealworms. Note: adult insects are more nutritious than larval forms.	

Data from Johnson-Delaney C. Marsupials. In: Meredith A, Johnson-Delaney C, editors. BSAVA manual of exotic pets. Fifth edition. A foundation manual. Quedgeley (United Kingdom): British Small Animal Veterinary Association; 2010. p. 103–26.

HAND-REARING

Marsupials are unique in that the embryo develops outside the uterus and depends on the teat secreting the appropriate milk for the age and maturation of the embryo. In captivity, this poses challenges and must approximate the natural process.

Macropods have 4 teats, although only one develops for each joey.

- As a survival strategy, some macropods have the capability of having 3 joeys at one time, each in a different stage of development.
- One joey can be out of the pouch but still nursing (young at foot, "YAF"), while another is developing in the pouch (pouch joey), and a third is waiting in utero as a result of embryonic diapauses.
- This occurrence can result in teats in 4 different stages of lactation: one undergoing regression from a previous joey, one for the YAF, one for the pouch joey, and one undeveloped teat for the joey yet to be born. The 2 teats that are actively lactating simultaneously produce milk of different compositions that are appropriate for each joey's stage of development.[19]

The role of the different milk during lactation has been studied. The mother progressively changes the composition of the major, and many minor, components of the milk.

- In contrast to eutherians, there is a far greater investment in development of the young during lactation and it is likely that many of the signals that regulate development of eutherian embryos in utero are delivered by the milk. This requires the coordinated development and function of the mammary gland because inappropriate timing of these signaling events may result in either limited or abnormal development of the young, and potentially a higher incidence of mature onset disease.

- Milk proteins play a significant role in these processes by providing timely presentation of signaling molecules and antibacterial protection for the young and the mammary gland at times when there is increased susceptibility to infection.[31]

Cross-fostering is rearing of young by a surrogate mother of a different taxon. In marsupials, this technique has been used to study lactation as well as pouch young growth and development. Data on cross-fostering are now available for 6 potoroid and 13 macropodid species.

- Studies have shown that female marsupials regulate milk composition and production irrespective of pouch young age, and that transfer of donor young to species with more immature or advanced mammary glands will result in a slowing or an acceleration of pouch young growth and development.
- The temperature and humidity within the pouch environment affects the duration of pouch life. Small pouch young tolerate short-term isolation from the pouch at a range of temperatures, provided high humidity is maintained throughout the period of isolation.
- Maintenance of pouch young at temperatures lower than those that occur in the pouch (23°C compared with 37°C) during isolation reduces the pouch young's BMR, oxygen consumption, and evaporative water loss and thus improves survival rates of very small pouch young.
- The success of these techniques in managing population genetics and accelerating breeding in donor species within the Macropodoidea are enhanced by post-partum estrus and mating after the removal of pouch young, and the reactivation and birth of the diapausing embryo.[32]

The effects on gastrointestinal maturation in tammar wallabies of providing younger pouch young with older-stage milk have been studied.

- There was a significant increase in pouch young weight when donor young were supplied with older-stage milk, possibly because of a higher concentration of lipid in milk from the more advanced mammary glands.
- However, no difference was found in stomach or small intestine development between young reared on the appropriate milk for age and those reared on milk for more advanced pouch young.[32]

The need for hand-rearing can occur as a result of health issues or death of the dam or if the dam throws the joey from the pouch as a result of stress. Artificial rearing of macropod joeys can be challenging. Commercial products for stage of development are available (Wombaroo; Perfect Pets Inc, Belleville, MI; **Box 3**).[33] Body measurements and not weight should be used along with species-specific growth charts to determine the joey's age. Artificial milk replacers designed for other species and whole milk from other species should not be used, because they often contain high levels of oligosaccharides (eg, lactose, sucrose). Because of previously described slower mechanism for digestion of these oligosaccharides in macropods, their use can result in severe problems, such as osmotic diarrhea, gastrointestinal bacterial overgrowth, and cataracts. More detailed information on hand-rearing macropods is available.[34]

METHODS

Orphaned joeys first need to be at a normal body temperature of 95 to 98.6°F (35–37°C) before feeding. The milk formulation should be chosen for the species and age class.

- A rule of thumb is to feed formula at 95°F (35°C).

Box 3
Artificial milk formulations specific for marsupials

Commercial marsupial formulations and nursing equipment:

Wombaroo Food Products, PO Box 151, Glen Osmond, SA 5064, Australia

US Distributors: Perfect Pets, Geoff Schrock, 23180 Sherwood Rd, Belleville, MI 48111; (734) 461-1362, Fax (734) 461-2858

Kangaroo Milk Replacer (for all macropods)

(<0.4, 0.4, 0.6, >0.7) key: less than 0.4, less than 40% pouch life complete

Possum Milk Replacer (for sugar gliders) (<0.8 for joeys with <80% pouch life complete; >0.8 for joeys with >80% pouch life complete)

Latex teats: STM: for small, in-pouch kangaroos, wallabies, possums

MTM: for in-pouch kangaroos, wallabies, koalas

TM: for out-of-pouch kangaroos, wallabies

SD: for possums, gliders

Biolac Milk Replacer for Marsupials

US Distributors: 675 Gooseberry Court, Lafayette, CO 80026; (303) 666-0924, Fax: (303) 666-0574. Australia: Geoff and Christine Smith, PO Box 93, Bonnyrigg, NSW 2177; 011 61 (02) 9823 9874

M100—early lactation milk

M150—mid lactation milk

M200—late lactation milk

M100-G—with galacto-oligosaccharides for furless joeys

T1—Long joey teat, hard or soft

T2—Long, fine teat, for very all orphans

T4—Short, fine teat, for sugar gliders

Data from Johnson-Delaney CA. Reproductive medicine of companion marsupials. Vet Clin North Am Exot Anim Pract 2002;5:537–53.

- Formulas should be made fresh, and utensils, teats, and bottles should be washed and sanitized after use.
- Unfurred animals are fed approximately every 2 to 3 hours and furred approximately every 4 hours. Frequency must be adjusted for the physical condition of the joey.
- Weak or dehydrated animals may require feedings every 2 hours.
- The amount of formula a joey should receive within a 24-hour period is related to its body weight and formula used. The rule of thumb is 10% to 20% of the body weight in formula every 24 hours, but no more than 20%.

Marsupial teats are shaped differently than those sold for domestic animals or humans. The hole in the teat must be small and can be made by piercing the teat several times with a hot needle. Alternatively, a syringe with a gastric feeding tube, feline urinary catheter, or intravenous catheter (needle removed) can be used to provide the small opening.

- Most joeys are best fed while in an artificial pouch, which can be fashioned from a sock, sweater, or towel.
- The environment needs to be dark, quiet, and without distractions. Covering the eyes with a hand during feeding may help.

- The joey should be weighed daily.
- When teeth have erupted and the joey is fully furred, small amounts of adult diet can be introduced.
- When the joey leaves the pouch for short periods, it should be provided adult food to investigate. Gradually decrease the formula feedings as the joey weans.
- Many companion marsupials will take formula or even plain water from a bottle long after weaning, which can facilitate the administration of medications and oral fluids if ever necessary.

SUGAR GLIDERS

Hand-rearing of sugar gliders has been documented.[13,35] Puppy Esbilac (Pet Ag, Hampshire, IL) has been used successfully to raise sugar gliders by one author, but there are recommendations to avoid Kitten Esbilac, goat's milk, cow's milk, or human milk replacer because of higher lactose contents than the canine formulation. This rearing recipe is included in **Box 4**.[33,35]

- Feed unfurred young every 1 to 2 hours, including throughout the night, and feed just-furred young every 4 hours.
- Gradually reduce the frequency to twice daily, then once daily, until the young are weaned.
- Guidelines for volume of milk to feed per day are shown in **Table 10** along with milestones and body weight with respect to age.[35]

Marsupial milk increases in energy at the time of pouch exit to provide for the young's increased energy demands of locomotion and thermoregulation. This change can be simulated by adding canola oil or rapeseed oil to the milk at the rate of 1 mL of oil per 20 mL of formula.[13]

- Juvenile sugar gliders usually lap readily from the tip of a syringe, or they can be taught to lap from a small plastic lid.
- At each feeding, measure and record milk intake.
- Measure body weight daily until the weight stabilizes, then weekly.
- Frequency of feeding and quantity of food can be adjusted to achieve a satisfactory growth rate.
- Start offering solids at about 100 days, at which time the young glider should weigh approximately 54 g, and wean at 130 days, when body weight is approximately 80 grams.[35]
- Pureed baby food with meat and vegetables or blended adult diet is a suitable starter food.[13]

Box 4
Puppy Esbilac formulation for sugar gliders

1 Scoop Puppy Esbilac powder (Pet Ag, Inc)

3 Scoops Pedialyte (initially, if dehydrated) or plain water (Abbott Laboratories, Abbott Park, IL)

Warm to body temperature, syringe feed one drop at a time every 2 h until furred.

Fully furred: feed every 3–4 hours

Once the eyes have opened, cease the night feedings.

At least twice daily or before feedings: stimulate urination and defecation by gently stroking the area of the cloaca and base of tail with a moistened cotton ball or swab.

Table 10
Growth and development of young sugar gliders (*P breviceps*) from southeast Queensland (Guidelines for hand-rearing based on wild glider development)

Age (d)	Weight (g)	Feed (mL per day)	Milestones
1	0.2	A few drops (author estimated for hand-rearing purposes)	Mouth and forelimbs most developed feature
20	0.8	A few drops (author estimated for hand-rearing purposes)	Ears free from head, papillae of mystacial vibrissae visible
35	2.0	1.0	Mystacial vibrissae (whiskers) erupt, ear pigmented. Realistic time to successfully hand-rear
40	3.0	1.5	Pigmentation starts on shoulder, eye slits present
60	12	3	Detaching from teat, fur emerging, dorsal stripe developing
70	20	4	Eyes open, fully furred, left in nest
80	35	6	Fur lengthens
90	44	7	
100	54	8	Emerging from nest, starting to eat solid foods
130	78		Weaned

Data from Barnes M. Sugar gliders. In: Gage LJ, editor. Hand-rearing wild and domestic animals. Ames (IA): Iowa State Press; 2002. p. 55–62.

MACROPODS

- An artificial formula has been used successfully. Wombaroo (Wombaroo Food Products, PO Box 151, Glen Osmond, SA, Australia) and Biolac (Biolac, Lafayette, CO) are commercially available marsupial milks with different concentrations of the major components to match the needs of joeys in different stages of development (see **Box 3**). These commercially available marsupial milks are low-lactose formulations.
- Start by diluting the formula with an oral rehydration electrolyte solution on the first 2 to 3 days to allow adjustment to the new formula. Half strength on day 1, two-thirds strength on day 2, three-quarter strength on day 3, and full-strength formula on day 4 is an example of a suitable regime.
- Unfurred joeys are fed every 1 to 2 hours.
- Recently furred young should be fed every 4 hours, and then the frequency of feeding should gradually be reduced to once or twice daily before weaning.
- Food intake should be measured and recorded at each feed. Simulate hand-raised young to urinate and defecate after each feed by gently wiping the cloaca with moistened cotton ball. Measure body weight daily until it has stabilized, then weekly.[33,34]

VIRGINIA OPOSSUMS

The National Opossum Society has published detailed infant diets, feeding instructions, and growth information for the Virginia opossum.[8] The basic formula can be made using either Esbilac or Multi-Milk (PetAg, Inc) at either 1:3 to 1:5 dilution with distilled water. Added to this is egg yolk, brewer's yeast, apple juice, or boysenberry low-fat yogurt.[36]

Another hand-rearing formulation has been used successfully to rear Virginia Opossums:

- Mix Puppy Esbilac, or Zoologic Milk Matrix 33/40 powder (all Pet Ag, Inc [1-800-323-0877 for product questions]) or Multi-Milk or Zoologic Milk Matrix 30/55 powder.
- One part Esbilac or Zoologic Milk Matrix 33/40 powder, $^1/_2$ part Multi-Milk or Zoologic Milk Matrix 30/55, 2 parts water. Mix by volume (ie, teaspoon, tablespoon, cup). If water quality is poor, use distilled water. Values shown are wet matter basis (percentage of mixed formula), 21.7% solids, 10.5% fat, 7.3% protein, 2.3% carbohydrates, 1.33 KCal/mL.[37]

By the time an opossum is 45 g, it can be taught to lap formula from a jar lid (**Fig. 10**). They will need to be encouraged.

- When the opossums are lapping regularly on their own, hand feeding can be reduced to once or twice a day or discontinued when they weigh 60 g or more. Formula needs to be thickened by adding ground or whole Purina Kitten Chow ("original formula" only; Nestle Purina PetCare, St. Louis, MO) that has been mixed with water.
- This mixture will be called "chow-pudding." Grind dry Purina Kitten Chow in a blender or food processor. Add a sufficient amount of water to give the chow a pudding-like consistency. Allow this to set in the refrigerator for approximately 10 minutes. It absorbs water faster when refrigerated.
- The whole consistency changes (there should not be any hard chunks). More water or more chow may be added to get the desired consistency. Thicken the formula with a small amount of the chow-pudding mix. It should resemble formula that has small particles of Kitten Chow throughout.
- As the joey becomes accustomed to the taste, increase the amount of the chow-pudding. Provide a lid of whole dry Purina Kitten Chow and another lid of Kitten Chow that has been soaked in water 5 to 10 minutes in whole form. Some animals eat the softer chow more readily. A shallow container of water should also be available. By the time the opossums weight 80 to 100 g, introduce the modified Jurgelski diet (**Box 5**). The diet composition is 33.2% solids, 3.3% fat, 13.9% protein, 11.2% carbohydrates equaling 21.2 KCal per tablespoon. Altering the amount of liver or using another brand of kitten food has and will

Fig. 10. Juvenile Virginia opossum eating out of a jar lid.

Box 5
Modified Jurgelski diet: precise measurements

Offer in the evening.

1 part ground, raw beef liver

9 parts Purina Kitten Chow pudding (ground dry chow mixed with enough water to give a pudding-like consistency)

To every cup of kitten chow pudding, add $^1/_4$ teaspoon pulverized calcium carbonate that equals 700–800 mg Ca per teaspoon.

Data from Taylor P. Opossums. In: Gage LJ, editor. Hand-rearing wild and domestic animals. Ames (IA): State Press; 2002. p. 45–54.

cause metabolic bone problems. The diet should be offered every evening. Some animals take longer than others to acquire a taste for this diet. When the opossum is consistently eating the modified Jurgelski diet, gradually add small quantities of various fresh fruits and vegetables (add one item at a time). Cut into bite-size pieces before offering them to the youngsters. The modified Jurgelski diet should constitute 90% of the total diet.[37]

In conclusion, much is known about the nutrition and dietary requirements of captive marsupials. The most important goal for clinicians is that there is enough information available from captive and field studies of the major species of marsupials (metabolic rates, effects of food habits, activity levels) to develop appropriate diets. Micronutrient components still need to be studied in many, but little should be left to guesswork, and diets should not be fed simply because the animal prefers certain food items. It is easy to overfeed captive marsupials.

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