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Serum Concentrations of Lipids, Vitamins A and E, Vitamin D Metabolites, and Carotenoids in Nine Primate Species at Four Zoos

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The purpose of this work was to measure important nutritional status parameters for captive primates, compare those with published data, and look for a link with diet. The nutritional status of nine captive primate species was examined using biochemical analysis. The species were spider monkeys (*Ateles geoffroyi*), colobus monkeys (*Colobus guereza*), sooty mangabeys (*Cercocebus torquatus*), Schmidt's monkeys (*Cercopithecus ascanius*), mandrills (*Papio sphinx*), baboons (*Papio cynocephalus*), chimpanzees (*Pan troglodytes*), orangutans (*Pongo pygmaeus*), and gorillas (*Gorilla gorilla*). Diet information was collected by survey and the estimated nutritional composition of the diet for each species at each institution was compared with non-human primate nutrient requirements. On the average, the captive primates received diets that met or exceeded recommended dietary guidelines for vitamins A, D, and E for non-human primates. Blood samples were collected from 94 primates held at Brookfield Zoo, Fort Worth Zoo, Lincoln Park Zoological Gardens, and North Carolina Zoological Park and analyzed for lipids, vitamins A and E, D metabolites, and carotenoids. Several species showed differences among zoos for some nutrients, but values from any one zoo were not consistently lower. When monkeys were compared with great apes, monkeys had lower serum total cholesterol, triacylglyceride, and measured LDL cholesterol levels, but significantly higher vitamin D metabolite levels. Species differences were found for serum A, E, and carotenoid levels (with the exception of lycopene). Some differences were seen in serum retinol, retinyl

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palmitate and g-tocopherol. The relatively large number of animals contributing to this database and the fact that the data were collected from four zoos provide a substantial base for comparing nutritional status. Comparisons of these serum levels with previously published values for selected primates and humans revealed some differences. Zoo Biol 18:551–564, 1999. © 1999 Wiley-Liss, Inc.

Key words: vitamin A; vitamin E; vitamin D; carotenoid; lipid; cholesterol

INTRODUCTION

Limited information is available on concentrations of lipids and vitamins in serum of wild and captive non-human primates. Determinations of circulating levels of lipids (total cholesterol, high-density lipoprotein (HDL) cholesterol, measured low density lipoprotein (LDL) cholesterol, and triacylglycerides), vitamins A and E, D metabolites and carotenoids can provide a base for examining the nutritional status of captive primates. The purpose of this study was to measure and compare these parameters in a relatively large number of primates representing nine species from multiple institutions in an attempt to link this information with diet composition.

Assessment of nutritional status is an important component in the successful conservation and propagation of captive and free-ranging primate populations. Animals require vitamins A, E, and D for normal growth, reproduction, and health [Machlin, 1984; Norman and Miller, 1984; Olson, 1984]. Carotenoids, such as b-carotene and lutein, have been found to be important in maintaining various immune functions [Chew, 1993]. Circulating levels of b-carotene have been utilized to assess malabsorption and nutritional status in humans [Miller, 1985].

Attempts have been made to assess the adequacy of an animal's diet by measuring serum/plasma concentrations. Gallo-Torres [1980] noted correlations between blood and tissue vitamin E and dietary vitamin E in several species of domestic and laboratory animals. Similarly, vitamin A concentrations are also accurately reflected by measuring hepatic vitamin A; however, liver biopsy is seldom employed because of its invasive nature. Therefore, analysis of circulating vitamin A levels often is used to assess the adequacy of dietary intake in zoo animals [Schweigert et al., 1991].

The relationship between diet and nutritional status in humans as assessed by serum analysis has been documented [Miller, 1985], but these data may not pertain to other primate species. Further, the relationship is not well documented in nonhuman primates except for some commonly used laboratory primates. Numerous studies examined specific nutrients or nutrition-related diagnoses; however, nutritional assessments of healthy animals are rarely found. Comparisons among species at several institutions can illustrate differences and potential problems. Thus comparing these data provides a more complete picture of nutritional status of captive primates.

METHODS

Diet Analysis

Diet information was obtained from each zoo's dietary records for each animal during the time period encompassed by this trial. Computer analysis (Animal Nutritionist software, N-squared Computing, Durango, CO) was used to calculate estimated nutrient content of the diet offered on a dry matter basis (DMB). Dietary

items were categorized in food groups primarily adapted from the American Dietetic Association [American Dietetic Association, 1986]. These included vegetables, starch, fruit, and miscellaneous categories (Table 1).

Exposure to ultraviolet (UV) light as sunlight was also noted.

Blood Collection

Blood from 94 primates at the Brookfield Zoo, Fort Worth Zoo, Lincoln Park Zoological Gardens, and North Carolina Zoological Park was opportunistically collected during physical examinations between January 1996 and December 1998 and chemically analyzed. These blood samples were drawn both for routine physical examinations of apparently healthy animals and necessary medical diagnostic procedures. Species included were spider monkeys (*Ateles geoffroyi*), colobus monkeys (*Colobus guereza*), sooty mangabeys (*Cercocebus torquatus*), Schmidt's monkeys (*Cercopithecus ascanius*), mandrills (*Papio sphinx*), baboons (*Papio cynocephalus*), chimpanzees (*Pan troglodytes*), orangutans (*Pongo pygmaeus*), and gorillas (*Gorilla gorilla*). All the analyses could not always be conducted on the serum collected from the animals. This was owing to the fact that the large amount of blood needed for all the samples was sometimes unavailable. The numbers of individuals from which serum was taken and analyzed are shown (Tables 2 and 3).

Of the 94 primates sampled, only eight individuals were diagnosed as having abnormal health status. These animals were not removed from the data because typical populations have animals that are unhealthy and therefore these data can be useful. However, it is important to note that the abnormal health status animals did have outlier values for many of the nutritional tests performed when compared with the ranges for their species. The animals with abnormal health status in the lipid data were two gorillas, two baboons, one colobus, and one mandrill. The animals with abnormal health status in the vitamin D data were one gorilla, two baboons, and two colobus. The animals with abnormal health status in the vitamin A and E data in-

TABLE 1. Food groups based on diet items offered to all species*

Nutritionally complete:
Mazuri New World Primate (Leafeater)
Mazuri Old World Monkey
High Protein Monkey Diet
(PMI Nutritional International, Brentwood, MO)
ZuPreem Primate Diet (canned)
ZuPreem Marmoset Diet (canned)
ZuPreem Priate Dry Diet
(Premium Nutritional Producs, Inc, Mission, KS)
Marion Leaf Eater Biscuits (Marion Zoological, Plymouth, MN)
Animal Spectrum Pro-Plus
Animal Spectrum High Fiber Primate Biscuits
(Animal Spectrum, North Platte, NE)
Fruits: apples, bananas, oranges, pears, grapefruit, grapes, cranberries, orange and grape juice
Vegetables: carrot, green beans, spinach, romaine, kale, celery, alfalfa hay, onion, cauliflower, green pepper, collard greens, parsley, cucumber, escarole
Starch: white potato, rice cakes, yam, corn, cereal, bread, sweet potatoes
Miscellaneous: multivitamins, baby food, sunflower seeds, raisins, peanuts, peanut butter, insects, egg, milk

*Items within categories were somewhat interchangeable (except nutritionally complete foods and multivitamins in the miscellaneous category) based on quantity designations.

Serum Concentrations of Lipids, Vitamins A and E, Vitamin D Metabolites, and Carotenoids in Nine Primate Species at Four Zoos. S.D. Crissey, J.E. Barr, K.A. Slifka, P.E. Bowen, M Stacewicz-Sapuntzakis, C. Langmen, A. Ward, K. Ange. *Zoo Biology.*

TABLE 2. Serum lipid and vitamin D metabolite levels in primates at Brookfield Zoo, Fort Worth Zoo, Lincoln Park Zoological Gardens, and North Carolina Zoological Park (mean ± SEM)

	Total cholesterol (mg/dL)	Tricylglyceride (mg/dL)	HDL cholesterol (mg/dL)	LDL cholesterol (mg/dL)	25(OH)D (ng/mL)	$1,25(OH)_2D_3$ (pg/mL)
Spider monkey	216.3 ± 18.82^{ab}	146.4 ± 27.53^{a}	45.2 ± 4.04^{b}	155.8 ± 15.39^{a}	19.5 ± 3.02^{bc}	246.0 ± 4.38^{a}
n	7	7	7	7	11	11
Colobus	138.2 ± 15.25^{bc}	58.5 ± 7.15^{ab}	54.0 ± 8.07^{ab}	74.8 ± 11.86^{ab}	16.6 ± 6.20^{c}	54.1 ± 10.58^{b}
n	6	6	6	6	10	10
Sooty mangabey	175.3 ± 7.08^{abc}	58.8 ± 10.48^{ab}	65.3 ± 8.57^{ab}	103.7 ± 3.28^{ab}	25.1 ± 5.41^{abc}	47.5 ± 16.72^{b}
n	4	4	4	4	4	4
Schmidt's monkey	NA	NA	NA	NA	17.0 ± 3.58^{bc}	15.3 ± 5.28^{b}
n					5	5
Mandrill	133.3 ± 9.28^{bc}	81.1 ± 13.02^{ab}	66.1 ± 7.01^{ab}	54.3 ± 7.15^{b}	37.5 ± 2.40^{a}	53.1 ± 11.47^{b}
n	9	9	9	9	8	8
Baboon	79.0 ± 4.97^{c}	48.7 ± 11.43^{b}	42.2 ± 3.50^{b}	29.2 ± 4.14^{b}	35.0 ± 5.17^{ab}	82.2 ± 13.97^{b}
n	6	6	6	6	6	6
Chimpanzee	176.6 ± 10.56^{abc}	140.6 ± 21.47^{a}	45.9 ± 4.34^{b}	108.3 ± 0.58^{ab}	13.1 ± 1.42^{c}	30.3 ± 4.80^{b}
n	12	12	12	12	14	14
Orangutan	169.3 ± 5.66^{abc}	64.5 ± 9.06^{ab}	40.7 ± 5.84^{b}	118.0 ± 0.83^{ab}	15.6 ± 3.92^{c}	22.6 ± 6.18^{b}
n	7	7	7	7	8	8
Gorilla	243.6 ± 14.35^{a}	112.2 ± 1.03^{ab}	83.3 ± 6.27^{a}	143.2 ± 12.86^{a}	16.7 ± 1.16^{c}	35.4 ± 4.17^{b}
n	25	25	25	25	25	25
Published values						
Callitrichidae	69 ± 4[3]	95 ± 7[3]	19 ± 7[3]	50 ± 3[3]	134.0 ± 23.8[1]	810 ± 119[1]
Cebidae	130–290	50–250	12.0–80.0[3]	–	134.0 ± 23.8[1]	810 ± 119[1]
Cerocopithecidae	42–239[2,3]	15–97[2,3]	11–122[2,3]	–	33.8 ± 5.3[1]	61 ± 5[1]
Great apes	145–311[2]	27–125[2]	37–129[2]	–	33.8 ± 5.3[1]	61 ± 5[1]
Humans	150–250[4]	0–150[4]	>35[4]	<130[4]	15–30[5]	20–50[5]

[a,b,c,d]Means with different superscripts within a column differ significantly ($P < 0.05$).
[1]Adams et al., 1985; [2]Hainsey et al., 1993; [3]Loeb and Quimby, 1989; [4]Zeman, 1991; [5]Holick, 1999a.
NA, values are not available.

TABLE 3. Serum vitamin A and E levels (μg/dL) in primates at Brookfield Zoo, Fort Worth Zoo, Lincoln Park Zoological Gardens, and North Carolina Zoological Park (mean ± SEM)

	Retinol	Retinyl palmitate	γ-Tocopherol	α-Tocopherol
Spider monkey	17.5 ± 1.32^{c}	0.8 ± 0.79^{b}*	35.0 ± 3.10^{bc}	1,348.2 ± 99.87^{a}
n	9	9	9	9
Colobus	47.7 ± 4.43^{abc}	3.3 ± 0.55^{b}	27.3 ± 3.31^{bc}	644.2 ± 70.86^{c}
n	11	11	11	11
Sooty mangabey	32.0 ± 3.84^{abc}	ND	101.5 ± 9.95^{a}	806.9 ± 34.42^{bc}
n	4		4	4
Schmidt's monkey	57.4 ± 10.96^{abc}	ND	25.4 ± 3.28^{bc}	767.8 ± 128.77^{bc}
n	5		5	5
Mandrill	33.5 ± 6.51^{abc}	5.0 ± 2.24^{ab}*	102.1 ± 13.12^{ab}	914.9 ± 62.08^{bc}
n	9	9	9	9
Baboon	46.0 ± 5.59^{abc}	8.6 ± 1.58^{ab}	58.2 ± 5.00^{b}	584.3 ± 50.85^{c}
n	6	6	6	6
Chimpanzee	85.1 ± 5.51^{a}	5.3 ± 0.97^{ab}*	24.3 ± 3.37^{bc}	1,034.4 ± 42.09^{ab}
n	14	14	14	14
Orangutan	69.2 ± 16.00^{ab}	4.4 ± 2.50^{ab}*	23.1 ± 1.98^{c}	757.9 ± 85.85^{bc}
n	7	7	7	7
Gorilla	73.3 ± 8.88^{a}	11.2 ± 1.34^{a}	41.9 ± 35.7^{bc}	993.5 ± 65.2^{b}
n	27	27	27	27
Published values				
Great apes	68 – 80[1]			510 – 720[1]
Humans	66 – 74[3]		135 ± 70[4]	882 ± 284[4]

^{a,b,c,d}Means with different superscripts within a column differ significantly ($P < 0.05$).
*Some values were not detectable.
[1]Ghebremeskel et al., 1988; [2]Brush and Anderson 1986; [3]Stacewicz-Sapuntzakis et al., 1987; [4]Behrens and Madere, 1986.
ND, not detected.

cluded one gorilla, two baboons, and three colobus. The baboons had several range outliers when analyzed for vitamins A and E, D metabolites, and lipids. The gorillas only had one outlier and that was when analyzed for carotenoids. The colobus showed several range outliers when analyzed for vitamins A and E and D metabolites. The mandrill did not show any range outliers.

The primates were fasted overnight and chemically immobilized before drawing blood. The veterinary staff then drew venous blood into tubes that did not contain anticoagulants. The protocol was performed under the guidelines of the Brookfield Zoo Animal Care and Use Committee. Serum was separated by centrifugation, wrapped in foil as appropriate to protect light-sensitive substances, labeled, and frozen for an average of 6 months at –80°C until thawed for analysis.

Blood Analyses

Total cholesterol [Allain et al., 1974; Beckman-Coulter, Inc., 1997], triacylglycerides [Bucolo and David, 1973; Beckman-Coulter, 1997], and HDL cholesterol [Rifai and Warnick, 1994; Beckman-Coulter, Inc., 1997; Sigma Diagnostics, 1997] concentrations were measured at Loyola University Medical Center (Maywood, IL) using the Synchron Delta CX7 Analyzer (Beckman-Coulter, Inc., Brea, CA). LDL cholesterol was calculated using the Friedewald equation [Friedewald et al., 1972] at the same laboratory.

Serum Concentrations of Lipids, Vitamins A and E, Vitamin D Metabolites, and Carotenoids in Nine Primate Species at Four Zoos. S.D. Crissey, J.E. Barr, K.A. Slifka, P.E. Bowen, M Stacewicz-Sapuntzakis, C. Langmen, A. Ward, K. Ange. *Zoo Biology.*

Samples were assayed for 25 hydroxy vitamin D [25(OH)D] and 1,25 dihydroxy vitamin D [1,25(OH)2D at the Mineral Metabolism Laboratory, Children's Memorial Hospital (Chicago, IL) using the method described by Reed et al. [1993].

Aliquots of thawed serum were analyzed for vitamin A (retinol and retinyl palmitate), vitamin E (a- and g-tocopherol), and carotenoids (a- and b-carotene, lutein/zeaxanthin, lycopene, b-cryptoxanthin, and canthaxanthin) by high-performance liquid chromatography at the University of Illinois, Chicago, using the method described by Stacewicz-Sapuntzakis et al. [1987]. Cis/trans isomers of the carotenoids were not separated.

Statistical analyses were performed using the SPSS computer software package (SPSS for Windows, Rel. 8.0.0 1997; SPSS Inc., Chicago, IL) analysis of variance, and Bonferroni's test for post hoc multiple comparisons with *P* levels set at 0.05. Means for species were calculated from single values for each individual. Most animals were sampled only once, but for those with multiple samples, a mean value was calculated before performing statistics. Statistical tests performed included comparisons for species, institution, and monkeys versus great apes. Comparisons were not performed to determine gender or age differences.

RESULTS

Diet Assessment

Group housing of the animals made it impractical to determine individual daily consumption. It was assumed that, over time, each animal consumed an equal portion f the total diet offered to the groups. An array of diets was offered at each institution. Table 4 illustrates the diet composition by food group. The contribution in the diet of nutritionally complete foods ranged from 8% to 36% (as fed basis). Multivitamins were given to the majority of gorillas and chimpanzees and to some of the orangutans and mandrills. It is important to note that these multivitamins did not appear to provide significant contributions to the parameters tested, and in fact most of the animals supplemented did not have any nutritional differences compared with those who were not.

None of the primates at Brookfield Zoo received ultraviolet (UV) light exposure except baboons. Sampled species at the other institutions received varying amounts of UV light through natural sunlight exposure, with the exceptions of sooty mangabeys, mandrills, and most colobus.

TABLE 4. Food group composition (in percentage as fed) of nine primate species' diets at Brookfield Zoo, Fort Worth Zoo, Lincoln Park Zoological Gardens, and North Carolina Zoological Park

	Nutritionally complete	Vegetable/ leafy	Starch	Fruit	Miscellaneous
Spider monkey	24	53	3	20	0
Colobus	17–34	36–54	4–12	10–16	0–2
Sooty mangabey	23	53	20	0	4
Schmidt's monkey	21	41	12	26	0
Mandrill	15–31	38–57	5–18	18–21	0–4
Baboon	24	48	5	21	2
Chimpanzee	8–34	36–57	5–15	20–24	0
Orangutan	8–11	61–73	8–11	8–20	0–1
Gorilla	8–36	40–70	3–10	10–33	0–4

Serum Concentrations of Lipids, Vitamins A and E, Vitamin D Metabolites, and Carotenoids in Nine Primate Species at Four Zoos. S.D. Crissey, J.E. Barr, K.A. Slifka, P.E. Bowen, M Stacewicz-Sapuntzakis, C. Langmen, A. Ward, K. Ange. *Zoo Biology.*

Table 5 presents an estimate of the nutrient composition of diets offered. The primary source for the majority of essential nutrients in the diets was the nutritionally complete food items in canned or biscuit form. Based on estimates of nutrient composition and comparison with NRC guidelines for non-human primates [NRC, 1978], the diets offered met or exceeded the probable requirements for vitamins D, A, and E. The only possible exception was vitamin D, which was offered in lower amounts to some of the colobus monkeys. Excessive levels were not found, although vitamin A appeared high in some of the diets. This is most likely due to the b-carotene contributions to the vitamin A values in the computer database.

Blood Analyses

Lipid and vitamin D metabolite levels are listed by species and compared with published data (Table 2). The levels are pooled among institutions. It can be seen that there were significant differences among species for all measures. Gorillas had the highest serum total cholesterol levels and were in the highest ranges for triacylglycerides, HDL cholesterol, and measured LDL cholesterol.

When animals were grouped taxonomically as great apes or monkeys, monkeys had significantly ($P < 0.05$) lower serum total cholesterol, triacylglyceride, and measured LDL cholesterol levels. No significant differences were found in HDL cholesterol concentrations between monkeys and great apes. Spider monkeys had higher 1,25(OH)2D concentrations than all other primates ($P < 0.05$). The great apes had the lowest levels of 25(OH)D concentrations.

Serum concentrations of vitamins A and E are shown in Table 3 along with published primate and human values. Significant differences were found among species. Some differences between monkeys and great apes ($P < 0.05$) were seen in retinol and retinyl palmitate concentrations. Spider monkeys had the lowest levels of both retinol and retinyl palmitate, whereas chimpanzees and gorillas had the highest levels of retinol and retinyl palmitate, respectively.

Carotenoid levels (with the exception of lycopene) were different among spe-

TABLE 5. Calculated composition of diets fed to primates at Brookfield Zoo, Fort Worth Zoo, Lincoln Park Zoological Gardens, and North Carolina Zoological Park on a dry matter basis

	n	Fat (%)	Vitamin D[1] (IU/g)	Vitamin A[2] (IU/g)	Vitamin E[3] (mg/kg)
Spider monkey	11	4.9	4.1	14.0	137
Colobus	10	4.4–8.0	1.1–3.5	34–59	142–219
Sooty mangabey	4	10	4.2	61	74
Schmidt's monkey	5	4.7	3.0	115	102
Mandrill	9	5.9–9.2	4.9–8.0	21–41	74–93
Baboon	6	7.4	4.9	41	74
Chimpanzee	14	3.6–5.1	2.8–5.8	32–105	56–287
Orangutan	8	4.2–4.7	2.3–2.6	22–168	45–123
Gorilla	27	2.4–5.1	2.3–4.6	30–77	71–127
NRC, 1978		NA	2.22	13.9	55.6

[1]Vitamin D in the analyzed diets was primarily D3, with some diets containing small amounts of D2.
[2]Vitamin A in the analyzed diets was retinol, carotenoids or both.
[3]Vitamin E in the analyzed diets was either α-tocopherol or total tocopherol, depending on the source of the data.
NA, values are not available.

Serum Concentrations of Lipids, Vitamins A and E, Vitamin D Metabolites, and Carotenoids in Nine Primate Species at Four Zoos. S.D. Crissey, J.E. Barr, K.A. Slifka, P.E. Bowen, M Stacewicz-Sapuntzakis, C. Langmen, A. Ward, K. Ange. *Zoo Biology.*

cies (Table 6; $P < 0.05$). Differences ($P < 0.05$) between monkeys and great apes were seen in serum a-carotene concentrations. b-carotene levels were highest in sooty mangabeys. They were more than 100 times those of chimpanzees and gorillas. Lycopene was undetectable in the serum of many animals.

DISCUSSION

Lipids

Plasma cholesterol levels can be influenced by dietary cholesterol intake, endogenous synthesis, excretion, and reabsorption of cholesterol. In humans, the majority of plasma cholesterol appears to be reflective of the rate of endogenous synthesis, and 75% of plasma cholesterol is located in the LDL cholesterol fraction. Further, a high serum LDL cholesterol level has been proposed as a positive risk factor for coronary heart disease [Zeman, 1991]. Gorillas and spider monkeys in this study had the highest levels of serum cholesterol and LDL cholesterol, and gorillas had consistently higher levels than reported as normal for humans [Zeman, 1991]. However, these levels fall within the ranges previously published [Hainsey et al., 1993]. Captive gorillas with diet-related health problems such as obesity and atherosclerosis, have been reported to have high plasma cholesterol concentrations [Crissey and Allen, 1986]. The existence of a cause-and-effect relationship between high circulating total cholesterol and LDL cholesterol concentrations and an animal health risk has not been established. It is interesting to note that there were not any differences in lipid values for animals in this study when compared with ISIS ranges, which are all raw data from captive animals.

Squirrel monkeys and baboons have shown evidence of genetic differences in the lipemic response to dietary fat and cholesterol intakes. This response appears to vary among species, and most likely among individuals as well [McGill and Kushwaha, 1995]. In humans, it has been shown that many individuals have feedback control mechanisms that result in little change in plasma total cholesterol when dietary cholesterol increases [McNamara et al., 1987]. In contrast, dietary cholesterol and type of fat had different effects on serum lipoproteins in baboons [McGill et al., 1981]. The dominant contemporary opinion seems to be that the most powerful dietary determinant of blood cholesterol level is saturated fat intake [Hegsted et al., 1993]. Nutrient composition estimates in this study were limited to fat content of the diet offered and did not include dietary concentrations of monounsaturated, polyunsaturated, and saturated fats. Thus, future work using controlled diets coupled with serum sampling will be necessary to provide additional insight into the significance of the lipid levels found in primate serum.

Vitamin D

Colobus monkeys were offered the lowest range of vitamin D per gram of food with two zoos providing diets that did not meet NRC recommendations for primates. Only one group had outdoor sunlight exposure, and this was for only part of the year. However, these animals did not exhibit the lowest serum 25(OH)D and 1,25(OH)2D. The colobus monkeys and several other species did, nonetheless, have low 25(OH)D values. In all species except the baboons, mandrills, and sooty mangabeys, 25(OH)D was low compared with humans. Of all species, chimpanzees had the lowest serum levels of 25(OH)D, despite dietary levels above NRC recom-

Serum Concentrations of Lipids, Vitamins A and E, Vitamin D Metabolites, and Carotenoids in Nine Primate Species at Four Zoos. S.D. Crissey, J.E. Barr, K.A. Slifka, P.E. Bowen, M Stacewicz-Sapuntzakis, C. Langmen, A. Ward, K. Ange. *Zoo Biology.*

TABLE 6. Serum carotenoid levels (μg/dL) in primates at Brookfield Zoo, Fort Worth Zoo, Lincoln Park Zoological Gardens, and North Carolina Zoological Park (mean ± SEM)

	Lutein + zeaxanthin	β-Cryptoxanthin	Lycopene	α-Carotene	β-Carotene	α-Cryptoxanthin
Spider monkey	45.1 ± 5.71^{bc}	5.2 ± 0.42^{b*}	0.3 ± 0.17^{a*}	77.7 ± 16.65^{ab}	54.6 ± 10.93^{bc}	11.3 ± 1.38^{b}
n	9	9	9	9	9	9
Colobus	10.4 ± 2.45^{d}	0.9 ± 0.32^{bc*}	0.7 ± 0.30^{a*}	2.1 ± 1.09^{d*}	6.5 ± 3.19^{d}	2.4 ± 0.49^{c}
n	11	11	11	11	10	7
Sooty mangabey	101.4 ± 8.99^{a}	12.8 ± 1.82^{a}	ND^{a}	97.2 ± 16.89^{a}	166.8 ± 24.78^{a}	14.9 ± 1.89^{ab}
n	4	4		4	4	4
Schmidt's monkey	68.3 ± 13.41^{abc}	2.9 ± 0.70^{bc}	ND^{a}	2.1 ± 0.71^{d*}	14.1 ± 5.92^{cd}	6.3 ± 0.80^{bc}
n	5	5		5	5	5
Mandrill	10.3 ± 4.44^{d}	0.9 ± 0.12^{bc}	0.9 ± 0.50^{a*}	2.2 ± 1.46^{d*}	2.9 ± 1.35^{d}	1.7 ± 0.20^{c}
n	9	9	9	9	9	9
Baboon	29.8 ± 3.79^{cd}	5.3 ± 0.85^{b}	ND^{a}	6.3 ± 1.71^{cd}	15.6 ± 3.41^{cd}	9.5 ± 1.13^{bc}
n	6	6		6	6	6
Chimpanzee	27.9 ± 4.92^{cd}	0.3 ± 0.11^{c*}	0.7 ± 0.16^{a*}	0.9 ± 0.22^{d*}	0.9 ± 0.32^{d*}	2.5 ± 0.48^{c*}
n	14	14	14	14	14	14
Orangutan	77.8 ± 14.05^{ab}	13.8 ± 3.69^{a}	9.0 ± 8.24^{a*}	42.1 ± 22.37^{bc}	71.6 ± 33.79^{b}	21.7 ± 6.83^{a}
n	7	7	7	7	7	7
Gorilla	36.9 ± 5.53^{c}	0.6 ± 0.15^{c}	0.7 ± 0.17^{a*}	1.0 ± 0.21^{d*}	0.80 ± 0.16^{d*}	3.0 ± 0.49^{c*}
n	27	27	27	27	27	27
Published values						
Cebidae					0.8–10.1[1]	
Cercopithecidae					2.0–9.8[1]	
Humans	18–19[2]	9–10[2]	19–21[2]	2.9–3.8[2]	17–24[2]	9–10[2]

[a,b,c,d]Means with different superscripts within a column differ significantly ($P < 0.05$).
[1]Snodderly et al., 1990; [2]Stacewicz-Sapuntzakis et al., 1987.
*Some values were not detectable.
ND, not detected.

Serum Concentrations of Lipids, Vitamins A and E, Vitamin D Metabolites, and Carotenoids in Nine Primate Species at Four Zoos. S.D. Crissey, J.E. Barr, K.A. Slifka, P.E. Bowen, M Stacewicz-Sapuntzakis, C. Langmen, A. Ward, K. Ange. *Zoo Biology.*

mendations. All primate groups, except Schmidt's monkeys with very low levels, were within or above the human range for 1,25(OH)2D, but some were below other published primate values [Adams et al., 1985; Holick, 1999a]. Circulating serum 25(OH)D is the major circulating form of vitamin D and is considered the most valuable indicator of status owing to its steady state in the circulation. 1,25(OH)2D is the biologically active form and may reflect immediate intake or sun exposure [Rucker and Morris, 1997; Holick, 1999b].

Human requirements for vitamin D are met if they are exposed to adequate sunlight. However, it is still considered an essential dietary nutrient because people do not always have adequate sunlight exposure [NRC, 1989]. Extent of exposure to UV light may have had a substantial impact on circulating vitamin D metabolites in this study and may account for some of the variations not associated with diet. However, because actual UV light exposure was not measured, this remains unknown. Still, most of the primates received either multivitamins containing vitamin D3 and/or UV exposure, but serum 25(OH)D levels remained below published levels for humans and other primates. Mandrills and sooty mangabeys received no UV exposure yet had higher vitamin D metabolite levels than most other primates. The baboons that were exposed to sunlight also had higher circulating vitamin D metabolites. Additionally, more than 80% of all gorillas received a daily human multivitamin with vitamin D3, thus low levels of serum vitamin D metabolites may indicate a more complex problem than merely dietary.

Vitamin D metabolite levels in primates in a previous study were grouped by New World Monkeys versus Old World monkeys and apes [Adams et al., 1985]. Data from our study revealed that great apes had lower serum 25(OH)D levels than many Old World monkeys, thus the two should not be grouped together. Additionally, Adams et al. collected blood from primates housed at a single zoo, whereas the study reported here gathered samples nationwide from four zoos, generating a much larger sample size (94 versus 44 individuals). Although spider monkeys in the current study showed an elevation of circulating 1,25(OH)2D levels, these values were lower than those previously reported for New World monkeys [Adams et al., 1985]. Interestingly, the animals in the Adams study were fed from 6 to 8.8 IU/g dry diet of vitamin D3 compared with the non-human primate requirement of 2.22 IU/g diet, whereas the spider monkeys in this study were fed approximately 4.1 IU/g dry diet. Thus, the high levels in the Adams et al. study could have been a reflection of diet. When exposed to UVB light, New World primates had increased serum 25(OH)D and 1,25(OH)2D levels [Gacad et al., 1992]. The 11 spider monkeys in this study had much lower values than these previously reported data and possessed 25(OH)D much below the values reported for either humans or non-human primates. The reasons could be a combination of diet levels and no exposure to UV light. No clinical signs of vitamin D deficiency were evident during the study.

Vitamin A

Vitamin A concentrations in diets offered to all primate species in all four institutions met or exceeded the probable nutrient requirement [NRC, 1978]. All species, with the exception of great apes, were below previously reported human and primate levels for circulating retinol [Brush and Anderson, 1986; Stacewicz-Sapuntzakis et al., 1987; Ghebremeskel and Williams, 1988]. Sample size was considerably smaller in the previous studies: three orangutans [Brush and Anderson,

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1986] and two chimpanzees, one gorilla, and two orangutans [Ghebremeskel and Williams, 1988].

All species sampled had serum concentrations above 15 mg/dL, a reported deficiency level for humans [NRC, 1989]. In past studies, it was postulated that serum retinol levels of New World primates were lower than those of Old World primates; however, the differences in that study could not be explained by diet. Instead, it was implied that the differences in amounts of circulating retinol binding protein (RBP) have a stronger effect on serum retinol levels than does diet [Rogers et al., 1993]. RBP was not analyzed in this study, but retinol levels were still different. Because spider monkeys were the only representative of New World species, the comparison was not highlighted in this study. However, the spider monkeys did have the lowest circulating levels of retinol. This is not unexpected considering they were fed the diet lowest in retinol. In contrast to the low levels of circulating retinol, circulating retinyl palmitate has been reported to indicate excessive dietary vitamin A in some animals [Schweigert et al., 1991]. Retinyl palmitate concentrations present in some animals in this study were not elevated and often were undetectable.

Vitamin E

All diets provided to primate species met or exceeded probable nutrient requirements for non-human primates [NRC, 1978]. Serum levels of α-tocopherol can be correlated to dietary intake [Willett et al., 1983]. However, the ratio of tocopherol to cholesterol plus triacylglycerides is as useful as the ratio of tocopherol to total lipids for evaluating tocopherol status in humans [Draper, 1980; Thurnham et al., 1986]. Of all the species sampled for both a-tocopherol and lipids, baboons had the lowest a-tocopherol levels and overall lowest total lipid levels. The spider monkeys, chimpanzees, and gorillas were recorded with the highest lipid levels and accordingly the highest α-tocopherol levels. It is important to note that many of these primates were also offered diets very high in tocopherol concentrations. Diets high in polyunsaturated fatty acids (PUFA) have been shown to increase vitamin E requirements because of its protective role in PUFA antioxidation [Draper, 1980]. In this study, most circulating α-tocopherol levels were greater than those reported previously for baboons and chimpanzees [Brush and Anderson, 1986]. The animals in the current study appeared to have elevated α-tocopherol concentrations when compared with baboons that had undetectable α-tocopherol levels [Brush and Anderson, 1986]. The differences in vitamin E status could have been the higher levels of dietary vitamin E in this study, but these comparisons could not be made owing to the inability to determine individual animal intakes. The importance of γ-tocopherol, which was present in differing levels, is not known.

Carotenoids

The dietary intake of carotenoids was not measured in this study and therefore a dietary link to circulating carotenoids cannot be established. However, carotenoids can be important for immune function [Chew, 1993], and establishing normal circulating levels may become increasingly important. The array of serum carotenoids reported here provides a good indication of levels found in a large number of captive primate species. These parameters have yet to be reported for most primates. Table 6 shows that in primates other than colobus monkeys and mandrills, lutein+zeaxanthin levels were higher than human levels [Stacewicz-Sapuntzakis et al., 1987]. Cryptox-

Serum Concentrations of Lipids, Vitamins A and E, Vitamin D Metabolites, and Carotenoids in Nine Primate Species at Four Zoos. S.D. Crissey, J.E. Barr, K.A. Slifka, P.E. Bowen, M Stacewicz-Sapuntzakis, C. Langmen, A. Ward, K. Ange. *Zoo Biology.*

anthin matched or exceeded reported human levels in only the sooty mangabeys and orangutans. Lycopene concentrations for all primates sampled were lower than those for humans, including a number that were not detectable. This is not surprising given that there are few sources of lycopene (grapefruit, egg yolk) in the diets fed to these animals. α -Carotene matched or exceeded human levels in all but Schmidt's monkeys, chimpanzees and gorillas. β-Carotene was below human values in most primates but higher in spider monkeys, sooty mangabeys, and orangutans. About half the primates sampled had lower cryptoxanthin than human levels. Given that dietary carotenoid levels were not analyzed in this study, the effect of diet on circulating carotenoids cannot be determined. However, there were dietary carotenoids present in the vegetable and starch food groups offered to the animals, and these food groups made up a considerable proportion of many of the diets.

Diet Indications

Linking diet composition to nutritional status can be difficult. The diets provided allowed the animals to meet their nutrient requirements. The non-human primate publication [NRC, 1978] was used as a guideline in this report, and although it requires updating, it was useful as a comparison for diets offered. However, other factors can affect nutrient intake.

Dominance issues and diet selection may be major factors influencing diet intake. Although the animals were offered a nutritionally balanced diet, they were group fed. Thus, it is probable that the more dominant animals may have preferentially selected certain food items, such as fruits, which are not as nutritionally complete as the primate biscuit [Crissey et al., 1995]. As a consequence, these individuals may have a lower nutritional status. Despite labels with guaranteed nutrient analysis, actual nutrient content of food products may vary substantially in batches made with different lots of natural ingredients [Newberne, 1975]. These variations may add inconsistency to the nutrient content of the diet. Additionally, animals may obtain unquantified nutrients from their environment. They can do this in various ways including drinking water, consuming browse or grass, and cutaneous vitamin D synthesis on exposure to UV light. The nutrients in the diet also must be present in a chemical form available to them for absorption and metabolism.

Gender, time of year, disease, immobilization procedure, and method of sample preparation could affect the concentrations of the measured serum constituents [Franzmann, 1985]. Conversely, other studies reported no significant effects of age and sex on serum concentrations of vitamins A and E, and total cholesterol in captive gorillas [McGuire et al., 1989]. Factors such as activity, growth, pregnancy, and lactation may alter nutrient requirements or utilization [Oftedal and Allen, 1996], and some of these factors may account for the variation in the reported data.

However, given the numbers of animals in this study, as well as multiple sampling locations, collection of these data added significantly to the information base for assessing the nutritional status of captive primates.

CONCLUSIONS

This study presents the lipid, vitamin A and E, and D metabolite status in 94 animals representing nine captive primate species. This information provides a substantial base of new data including:

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1. Vitamins A, E, and D in prepared diets fed to captive primates generally met or exceeded dietary nutrient recommendations established for non-human primates by the NRC.

2. There were significant differences among species with respect to a number of circulating nutritional parameters.

3. There were nutritional parameter differences in the data presented in this study when compared with published data that used both fewer animals and species.

4. Circulating lipids appeared high in some species, especially the gorillas, and were correlated with vitamin E levels.

5. Low levels of circulating vitamin D metabolites and low levels of carotenoids were seen in some species compared with human values.

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Serum Concentrations of Lipids, Vitamins A and E, Vitamin D Metabolites, and Carotenoids in Nine Primate Species at Four Zoos. S.D. Crissey, J.E. Barr, K.A. Slifka, P.E. Bowen, M Stacewicz-Sapuntzakis, C. Langmen, A. Ward, K. Ange. *Zoo Biology.*

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Serum Concentrations of Lipids, Vitamins A and E, Vitamin D Metabolites, and Carotenoids in Nine Primate Species at Four Zoos. S.D. Crissey, J.E. Barr, K.A. Slifka, P.E. Bowen, M Stacewicz-Sapuntzakis, C. Langmen, A. Ward, K. Ange. *Zoo Biology.*