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Relations among Measures of Body Composition, Age, and Sex in the Common Marmoset Monkey (*Callithrix jacchus*)

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Few studies of body composition have been done in New World primates. In the study reported here, four methods of assessing body composition (body weight, anthropometry, labeled-water dilution, and total body electroconductivity) were compared in 20 marmosets, aged 0.96 to 7.97 years. Males and females did not differ in any measure ($P > 0.05$). Body weight ranged from 272 to 466 g, and body fat estimates varied from 1.6 to 19.5%. Strong positive correlations were observed between total body water and total body electroconductivity ($R^2 = 0.77$), body weight and fat-free mass (males $R^2 = 0.95$; females $R^2 = 0.91$), and body weight and fat mass (males $R^2 = 0.86$; females $R^2 = 0.85$; $P < 0.01$). Male and female slopes were equivalent ($P > 0.05$) for the regressions of fat and fat-free mass against body weight. Positive correlations also were observed between girth measures and fat-free mass ($R^2 = 0.48$ to 0.78) and fat mass ($R^2 = 0.60$ to 0.74; $P < 0.01$). A good second- order polynomial relationship was observed between age and fat-free mass for the combined sample ($R^2 = 0.64$). Results indicated that: subjects were lean; there was no sexual dimorphism relative to measures; body weight provided a reliable estimate of fat and fat-free mass; and within-subject body weight changes reflected a similar relationship between body weight and fat-free mass as did that across subjects.

An understanding of the relative body composition of an animal, particularly its fat and fat-free mass, is an important component of studies of normal metabolism and disease, particularly when examining the causes and effects of obesity. Rodent species are often used in such studies (1-5). However, non-human primates, particularly Old World species, also serve as important animal models in studies of metabolism and obesity (6-21). Although a few studies, such as that by Pond and Mattacks (16), have involved use of invasive/terminal techniques, most studies of body composition in non-human primates are longitudinal and/or non-terminal, and, therefore, involve use of relatively non-invasive techniques, such as total body water dilution, densitometry, and anthropometry. Some of those studies, such as those by Rawlins and co-workers (11) and Schwartz and Kemnitz (19) in 586 and 326 rhesus monkeys, respectively, of the free-ranging Cayo Santiago colony, have provided anthropometric and life history data for large colonies of Old World primate species.

Few studies on body composition have been conducted in New World primates, with most of the published data for one species, the squirrel monkey. Areas of research where body composition has been analyzed in this species include glucose tolerance testing (22), spontaneous obesity (23), and age and sex effects (23, 24). All of those studies involved use of carcass analysis to determine body composition other than body weight. To the authors' knowledge, there are virtually no other published body composition data other than body weight and anthropometric measures in other New World primates, particularly in the small-bodied species, such as marmosets and tamarins. Aside from routine recording of body weight in captive and wild populations, the relations of body weight, limb and body length measures, age, and sex have provided what we know about body composition in marmosets and tamarins (25-28).

Common marmosets (*Callithrix jacchus)* are small, monomorphic New World primates that are becoming increasingly important in a wide variety of biomedical research. However, little is published regarding body composition in this species. Our comparative study of body composition in common marmoset monkeys involved use of four techniques: body weight; length and girth anthropometric measures; total body electroconductivity; and labeled-water dilution. This study provides comparative estimates of fat and fat-free mass, while investigating the relations among age, sex, body weight, anthropometric measures, and total body water estimates by electroconductivity and labeled-water dilution in this species.

Materials and Methods

Animals. Twenty common marmoset monkeys (10 male, 10 female), ranging in age from 0.96 to 7.97 years, were studied. Subjects were housed as either breeding pairs or social groups consisting of a breeding pair with offspring, and met the recommendations of the *Guide for the Care and Use of Laboratory Animals*. Housing conditions were similar to those described in Clapp and Tardif (29). Experimental protocols were approved by our Institutional Animal Care and Use Committee. All females were non-pregnant and non-lactating (non-reproductive) at the time of body composition procedures. Subjects were fed a purified agar-based diet, ad libitum, providing 11 to 23% of energy from fat and 15 to 25% of energy from protein, and containing established target amounts of minerals and vitamins (Harlan Teklad Madison, Wis.). All subjects were part of a longitudinal study of nutritional effects on reproduction. Body composition measures

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were made at one time point for all but four subjects (two males, two females), for which measures were made at two time points with differing body weights.

For body composition procedures, food was withheld from subjects in the morning, then they were sedated with ketamine hydrochloride (10 mg/kg of body weight, i.m.), butorphanol (0.5 mg, i.m.), and atropine (0.10 mg, i.m.). Body weight (BW; g) was recorded, followed by total body electroconductivity, labeled-water dilution, and anthropometric procedures.

Total body electroconductivity. Total body electroconductivity functions on the principle that when a subject is introduced into a chamber surrounded by a radiofrequency coil, the change in impedance, or conductivity (1/resistivity), is related to the volume of water and electrolytes in the body. Therefore, the total body electroconductivity index (TOBEC) is used to estimate the fat- and bone-free mass (30, 31). This compartment of body mass has a significantly greater conductivity than does that of fat (32).

Subjects were positioned in the electroconductivity chamber in ventral recumbency with limbs tucked under the body. Animals were scanned three or four times, and mean TOBEC was used in the analysis. It is necessary for subjects to be perfectly still to obtain reliable TOBEC measurements. Movement in the chamber was indicated for two of the 20 animals, and therefore, data for those two were excluded, resulting in a sample size of 18 for this analysis.

Labeled-water dilution. Deuterium oxide (D_2O) dilution is currently the most common stable isotope technique used to measure total body water (33, 34). All 20 animals were used for labeled-water dilution analysis. For this study, D_2O (based on a minimal 1 ml/kg of body weight dosage) was administered via a size 8-F tube passed into the stomach, followed by two approximately 0.5 ml distilled water rinses. One-milliliter blood samples were collected via the femoral vein at two and 2.25 h after D_2O administration. Comparison of the two sequential blood samples indicated that D_2O equilibrium had occurred by 2 h. Infrared spectrometry was used to determine D_2O concentration in free water collected from thawed blood by heat distillation, as described (35). Estimated total body water (TBW; g) was calculated on the basis of dilution of D_2O in the circulation, and fat-free mass (FFM; g) was estimated from TBW. A hydration constant of 73% (34) or 73.2% (36) is generally used in FFM calculations. Studies reviewed by Schoeller (34) indicate a range of 70.7 to 76.3% for mammalian species (71.4 to 73.1% in the rat; 73.2% in the monkey; 72.8 to 73.7% in humans). A similar review is provided by Widdowson and Dickerson (37). The following calculation uses the assumption that 73.2% of FFM is water. Incorporation of a small percentage of D_2O into non-aqueous sites (exchange with non-aqueous hydrogen) can cause overestimation of TBW by 2 to 5% (33, 35). In addition, TBW is overestimated by the amount of D_2O (plus H_2O rinses) administered during the labeled-water dilution procedure. Therefore, correction factors of 3% and the total water dose are applied in the calculation of FFM from TBW as follows:

$$FFM = (TBW - 0.03\,(TBW) - \text{total water dose})/0.732$$

Total body fat (TBF; g) was then calculated as follows:

$$TBF = BW - FFM$$

Anthropometry. Body length and girth measurements were made, using metric vernier sliding calipers and a flexible metric tape measure, respectively. Length measurements were made three times and averaged; girth measures were made once. Each of 20 animals was measured for all scales except suprasternal-pubic length (n = 18; 10 males, 8 females). The measurements comprised suprasternal-pubic length (SSPL; cm), knee-heel length (KHL; cm), chest circumference (CHSTCIRC; cm), abdominal circumference (ABDCIRC; cm), arm circumference (ARMCIRC; cm), and thigh circumference (THICIRC; cm).

Statistical analyses. Statistical tests were performed, using SPSS for Windows, version 9.0. Two-sample *t*-tests were used to determine differences in means between male and female samples for measures of body composition when data were distributed normally and variances were equal; otherwise, Mann-Whitney and Wilcoxon procedures were used. Polynomial regressions were used for the statistical analyses of relations between age and measures of body composition, and simple linear regressions were used for examining relations among measures of body composition. The Student *t* distribution statistic was also used to compare slopes from the male and female regressions (38).

Results

Age and sex. Descriptive statistics of age for 10 males and 10 non-reproductive females are provided in Table 1. Examination of the cross-sectional relationship between age and measures of body composition for these 20 subjects combined indicated that FFM, BW, and TBF increased between approximately 1 year and 4 years of age, then began to decrease with increasing age thereafter. Fig. 1 illustrates the second-order polynomial relationship between FFM and age ($R^2 = 0.64$). Relations were also observed between BW and age ($R^2 = 0.54$) and TBF and age ($R^2 = 0.32$).

Descriptive statistics for BW, TBF, FFM, and length and girth measures for these males and females are provided in Tables 1 and 2. For males, BW varied from 277.7 to 465.9 g, FFM varied from 80.52 to 98.22%, and TBF derived from FFM estimation varied from 1.78 to 19.48%. For females, BW varied from 272 to 414.9 g, FFM varied from 84.67 to 98.38%, and TBF varied from 1.62 to 15.32%. Although females were significantly younger than males ($P < 0.05$), there were no significant differences between males and non-reproductive females for any of the measures of body composition, including anthropometry and BW ($P > 0.10$).

Relations among measures of body composition. A strong positive correlation was observed between BW and FFM for males ($R = 0.97$, $R^2 = 0.95$, slope = 0.64; $P < 0.01$) and females ($R = 0.95$, $R^2 = 0.91$, slope = 0.57; $P < 0.01$). Fig. 2 illustrates these regressions. A plot of BW by the residuals from the regression of these two variables for the overall sample ($R^2 = 0.95$) indicated that variances were equal across the range of BW. Fig. 3 illustrates the total sample regression line, with individual lines for multiple mea-

Table 1. Summary of age, body weight (BW), fat-free mass (FFM) and total body fat (TBF) for male (n = 10) and non-reproductive female (n = 10) marmosets

	Age (yrs)	BW (g)	TBF (g)	TBF (%)	FFM (g)	FFM (%)
Males						
Mean	3.83	363.99	39.53	10.05	324.46	89.94
SEM	0.66	21.98	8.47	1.72	14.49	1.72
Min	1.60	277.70	5.03	1.78	254.06	80.52
Max	7.97	465.90	90.77	19.48	381.25	98.22
Females						
Mean	2.43	321.10	22.99	6.63	298.11	93.37
SEM	0.58	13.67	6.40	1.56	8.16	1.56
Min	0.96	272.00	4.47	1.62	258.72	84.67
Max	6.39	414.90	63.58	15.32	351.32	98.38

Min = minimum; Max = maximum.

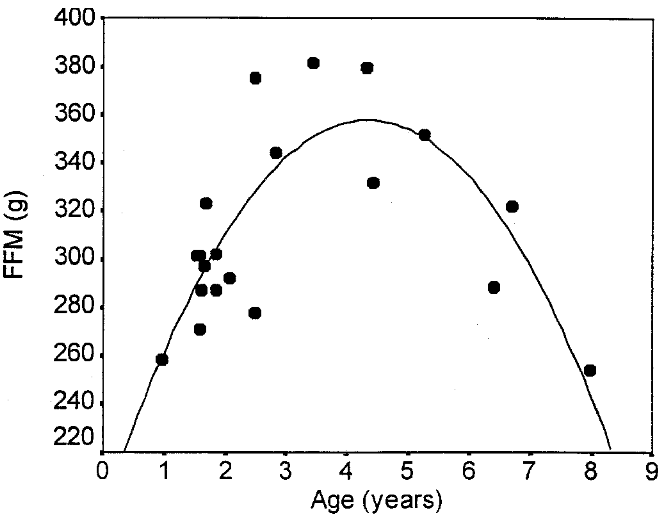

Figure 1. Polynomial regression of fat-free mass (FFM) against age in 20 marmosets (R^2 = 0.64).

Table 2. Summary of anthropometric data for male (n = 10) and non-reproductive female (n = 10, except where noted) marmosets

	ABDCIRC (cm)	ARMCIRC (cm)	CHSTCIRC (cm)	THICIRC (cm)	KHL (cm)	SSPL (cm)
Males						
Mean	9.86	5.70	13.89	7.49	6.73	14.02
SEM	0.38	0.19	0.35	0.27	0.06	0.22
Min	8.00	4.60	12.60	5.90	6.42	13.30
Max	11.70	6.50	15.40	8.30	7.05	15.40
Females						
Mean	8.74	5.41	13.07	7.29	6.73	13.79*
SEM	0.32	0.11	0.35	0.11	0.08	0.17*
Min	6.50	5.00	11.80	6.70	6.11	13.30*
Max	10.00	6.10	14.40	7.80	6.96	14.48*

ABDCIRC = abdominal circumference; ARMCIRC = arm circumference; CHSTCIRC = chest circumference; THICIRC = thigh circumference; KHL = knee-heel length; SSPL = suprasternal-pubic length; *n = 8.

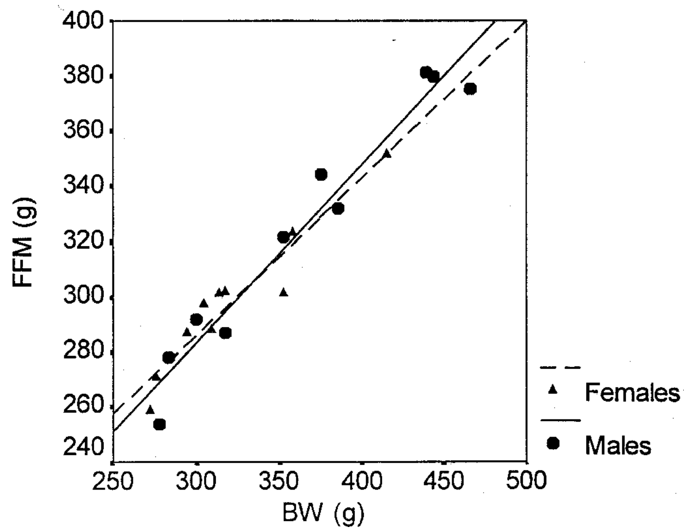

Figure 2. Linear regressions of FFM against body weight (BW) in 10 female (- - -) (R^2 = 0.91) and 10 male (—) (R^2 = 0.95) marmosets. Slopes were equivalent (R > 0.05).

sures for four animals at differing BW. This figure indicates that changes in FFM are related to changes in BW within subjects in a manner similar to that observed across subjects for the total sample. Similar to FFM, a strong positive correlation was observed between TBF and BW for males (R = 0.93, R^2 = 0.86, slope = 0.36; P < 0.01) and females (R = 0.92, R^2 = 0.85, slope = 0.43; P < 0.01), although the proportional variance was higher than that observed for FFM against BW. Fig. 4 illustrates this regression. There were no significant differences between male and female slopes for the FFM against BW or TBF against BW regressions (P > 0.05). No combination of BW and anthropometric measures, such as BW/SSPL, was superior to the simple BW to FFM or BW to TBF relation.

Strong positive correlations were observed between FFM and ABDCIRC (R = 0.88, R^2 = 0.78; P < 0.01), FFM and CHSTCIRC (R = 0.86, R^2 = 0.74; P < 0.01), FFM and ARMCIRC (R = 0.88, R^2 = 0.77; P < 0.01), FFM and THICIRC (R = 0.69, R^2 = 0.48; P < 0.01), TBF and ABDCIRC (R = 0.82, R^2 = 0.68; P < 0.01), TBF and CHSTCIRC (R = 0.86, R^2 = 0.74; P < 0.01), and TBF and ARMCIRC (R = 0.78, R^2 = 0.60; P < 0.01). Table 2 summarizes the anthropometric data. None of the anthropometric measures correlated more highly with FFM or TBF than did BW.

A strong positive correlation also was observed between TBW and TOBEC (R = 0.88, R^2 = 0.77, slope = 0.32; P < 0.01). Fig. 5 illustrates the significant linear relationship between these variables. A significant positive correlation also was observed between BW and TOBEC (R = 0.90; R^2 = 0.81; slope = 1.12; P < 0.01). However, the plot of BW by use of the standardized regression residuals indicated that the variances increased with increasing BW. The regression of TBW (from labeled-water dilution) against TBW predicted from a multiple regression, which included TOBEC and BW, resulted in a better linear relationship (R^2 = 0.94, P < 0.01) than that of TBW against TOBEC alone.

Discussion

The purpose of our study was not only to examine the relations among age, sex, and body composition in a sample of captive common marmosets, but also to provide a comparative study of the relations among various body composition techniques. These common marmosets, fed a purified moderate-caloric density diet, are lean, varying in estimated TBF from 1.6 to 19.5 (mean, 8.3)%. This is lower than mean percentage of fat mass reported for rats by use of carcass chemical analysis (1, 3, 5, 39). However, ranges in those studies overlap with those herein, and the results reported in literature vary considerably. Results reported for Old World monkeys are also variable, but overlap somewhat between ranges reported for percentage of body fat, although the upper ranges are greater than those for our marmosets (6, 12, 17). Captive primates are typically expected to be fatter than their free-ranging counterparts because they are often fed cafeteria-style diets. However, this study has indicated that common marmosets can be maintained in captivity on a purified diet and have body composition that is likely more closely related to that of free-ranging animals, given that the BW of animals in this study is similar to that of free-ranging animals (40).

Our investigation of changes in body composition relative to age was cross-sectional, and our sample did not contain enough older subjects for complete analysis of this relation. However, in the larger portion of the sample, subjects had an increase in FFM up until approximately 4 years of age. The 3 subjects beyond 5.5 years of age had lower FFM than did those between 3 and 4 years of age, and had equivalent FFM to that of younger subjects. This is suggestive of a pattern similar to that observed in humans, where

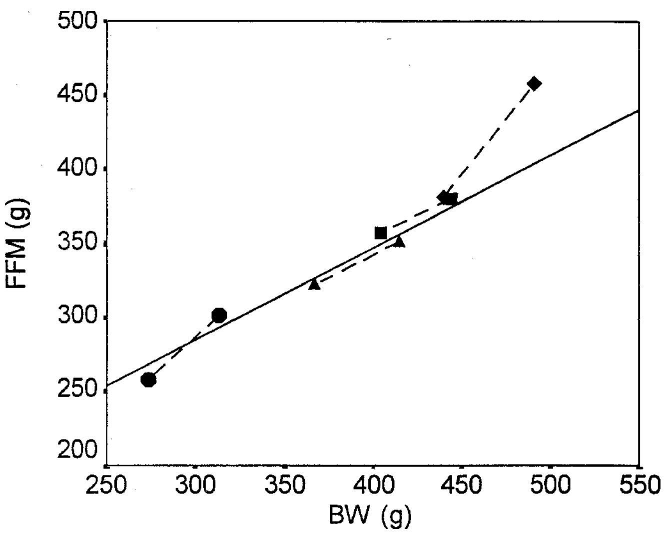

Figure 3. Repeated measures of FFM against BW for 4 marmosets (- - -) at differing body weight in comparison with the overall regression for the total sample of 20 marmosets (—). Notice that changes in FFM are related to changes in BW within subjects in a manner similar to that for the total sample.

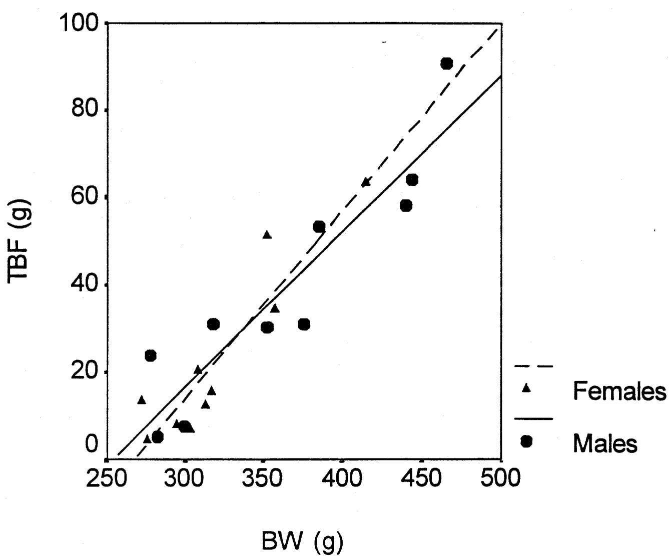

Figure 4. Linear regressions of total body fat (TBF) against BW in 10 female (- - -) (R^2 = 0.85) and 10 male (—) (R^2 = 0.86) marmosets. Slopes were equivalent (P > 0.05).

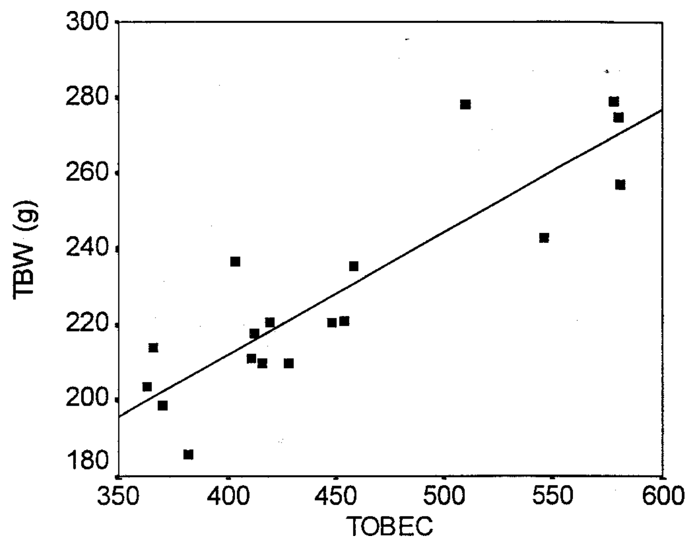

Figure 5. Linear regression of total body water (TBW) against total body electroconductivity index (TOBEC) in 18 marmosets (R^2 = 0.77).

FFM increases into early adulthood, plateaus and remains constant throughout adulthood, then decreases as they age (41, 42). Our data also suggested a pattern similar to that of FFM, which has been suggested for baboons (9, 43) and rodents as well (1).

Although non-reproductive females in this study were younger than males, they did not differ in measures of body composition or the relations among these measures. Previous studies indicate that common marmosets do not differ in BW or length measures (to our knowledge, there are no published data for other measures of body composition in this species) relative to sex (25-28). Therefore, this study provides additional evidence for the lack of sexual dimorphism in this species.

Our results are not directly comparable to studies of other animal species, but some apparent contrasts are notable. Baer and co-workers (44) indicated significant difference in BW between male and female rats, with no significant difference in TBF. Pitts (1), on the other hand, suggested a difference between males and females in BW and TBF, although experimental design was not completely equivalent between males and females relative to age and exercise regimens. Studies of body composition in sexually dimorphic Old World monkeys indicate not only significant difference in BW, but also in fat mass, between males and females (6, 17). Our research, in contrast, indicates that this small-bodied, non-sexually dimorphic species (relative to BW, length, and girth measures) does not exhibit sexual dimorphism in TBF and FFM.

A number of techniques have been done in studies of body composition. Although whole-carcass analysis is considered the most reliable and comprehensive method for directly determining body composition, it is time consuming, is obviously of no usefulness in non-terminal studies, and is not appropriate in longitudinal studies of metabolism, nutrition, aging, and reproduction. A comprehensive in vivo approach, the five-level model, separates body composition into atomic, molecular, cellular, tissue, and whole-body compartments (45, 46). A number of techniques are used to estimate components of these compartments (45). However, such a comprehensive in vivo approach is time consuming, and is not typically performed. Anthropometric indices are frequently used to estimate body composition, but these methods may suffer from high interobserver error (47). Total body water quantification, reflecting the molecular level of the five-level model, is frequently used in a two-compartment approach to estimate FFM. This method is more easily facilitated and less time consuming than are comprehensive in vivo methods, and provides a more direct and reliable estimate of body composition than do anthropometric measures. In this study, FFM was estimated, using TBW by labeled-water dilution in a two-compartment approach to body composition analysis. Other indirect methods were compared to determine their usefulness in predicting FFM by use of the labeled-water dilution method.

For this sample of captive common marmosets, BW provided as reliable an estimate of FFM or TBF as did any other indirect measure, when compared against our most direct method, TBW by labeled-water dilution. It is important to note that the strong relationships between BW and FFM and TBF are probably due to the leanness of this sample in particular. Low variation in length was observed in this sample. To determine whether increased size was associated with increased fatness, the relationships between TBF and KHL and SSL were examined. Relations were not observed, indicating that increased size was not associated with increased fatness in this sample. In addition, because of the low variation in length, inclusion of length measures did not improve the fit between BW and FFM or TBF. Although use of TOBEC in estimating TBW was not superior to use of BW, the prediction was improved by including combined measures of TOBEC and BW. Such a regression underestimated TBW for a subject that fell below the range of the sample BW measures. Therefore, our results are directly related to the size ranges of this sample. Lines between multiple samples from 4 animals were similar to the general regression line for BW and FFM estimated from TBW by labeled-water dilution for the whole sample, suggesting that within-subject weight changes in this population reflected the same relationship between FFM and BW as did comparisons across subjects. One exception was the subject having the highest BW and FFM (Fig. 3). This subject was longer in several body and limb length measures, compared with the subject with multiple measures closest to it, and generally was longer than all other subjects used in the total sample regression. Again, this indicates that the relation we observed between BW and FFM is likely subject to a range of body size most represented by our sample. For example, the relation between BW and FFM may not hold true for common marmoset populations that are much heavier on average, such as that described by Poole and Evans (48). Although it is unclear whether those animals were bigger in body size in terms of length measures, they were considerably heavier than animals in our sample, as well as free-ranging animals (40). It is important to note that their colony was maintained on a cafeteria-style diet in contrast to our purified diet. It is possible that the relation observed between BW and FFM in our sample of smaller marmosets would not be applicable to their sample of larger subjects.

It is assumed for our calculations that FFM is 73.2% water in males and non-reproductive females. The proportion determined by carcass chemical analysis has been reported to vary from approximately 71 to 74% across species, such as rodents, humans, and monkeys (34). However, adjustment in this proportion would not significantly affect the results that indicate these marmosets are lean for a primate.

This study applied a number of comparative methods for examining body composition in a captive sample of small anthropoid primates. We have documented that, in a captive colony of purified diet-fed marmosets that are lean, BW can provide a reliable estimate of body composition. Our results provide valuable information about callitrichid populations within a similar size range as we have described, and provide relevant information for studies concerning FFM and TBF relative to aging and obesity in small non-human primates. In addition, we have documented that common marmosets within a similar size range as we have described are monomorphic in yet another aspect, body composition.

Acknowledgments

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