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Fat-Free Mass and Total Body Water of Infants Estimated from Total Body Electrical Conductivity Measurements[1]

MARTA L. FIOROTTO, WILLIAM J. COCHRAN, AND WILLIAM J. KLISH

USDA/ARS Children's Nutrition Research Center, Department of Pediatrics, Baylor College of Medicine and Texas Children's Hospital, Houston, Texas 77030

ABSTRACT. Total body electrical conductivity measurements can be used in conjunction with suitable calibration curves to quantitate fat-free mass and total body water. A study was designed to evaluate whether calibration curves, derived from miniature piglets, can be used to translate total body electrical conductivity measurements of human infants into estimates of total body water and fat-free mass. Thirty-four, healthy 2-, 4-, 8-, and 12-wk-old infants were studied. A comparison of the physical dimensions of infants and piglets indicated no large discrepancies in their body geometries that would invalidate the calibration from this standpoint. Estimates of fat-free mass, fat, and total body water were evaluated by comparison with the body composition of reference infants of comparable description. There was excellent agreement between the total body electrical conductivity-derived estimates and reference body composition values, suggesting that the calibration procedure is adequate. Thus, the total body electrical conductivity technique can be used to estimate the body composition of normal young infants without subjecting them to risk or discomfort. (*Pediatr Res* 22: 417–421, 1987)

Abbreviations

TOBEC, total body electrical conductivity
FFM, fat-free mass
TBW, total body water
SFT, skinfold thickness
SEE, standard error of estimate

TOBEC measurements have been used to quantitate the FFM of adults (1). The measurement is based on the interaction between the conductive tissues of the body and a time-varying electromagnetic field (2). The magnitude of the interaction, reflected by the TOBEC signal, is proportional to the mass of the fat-free body; tissues with a low electrolyte and water content, such as adipose tissue, are relatively nonconductive and therefore interact minimally (3, 4). The interaction between the electromagnetic field and the conductive tissues is influenced also by their geometry and chemical composition, which, therefore, can independently alter the TOBEC signal (2, 4). The effect of these latter variables is complex for the human body because it is nonuniform in both its shape and conductive properties. Thus, a calibration is required which translates the TOBEC signal into a quantity of FFM. A calibration derived by relating the TOBEC signal of a group of reference subjects to their FFM determined by a standard method is the most satisfactory means to account for the effect of these nonuniformities of the human body. TOBEC measurements can also be calibrated for the estimation of TBW since the fluid component of the body is found almost exclusively in the FFM.

The requirement for an appropriate calibration has impeded the application of the TOBEC methodology to human infants because alternative techniques to determine their FFM accurately do not exist, and estimates of their TBW using stable isotopes are not always satisfactory (5). An animal model was used as an alternative approach for calibrating the infant TOBEC instrument. Adult rabbits were tested initially because their size was suitable (4), but although the measurements were precise, the FFM of infants was underestimated by the rabbit calibration curve (5). This discrepancy may have been attributable to differences in both the chemical composition and body geometry of rabbits and infants (6).

An evaluation of Hanford miniature piglets which included measurements of body composition and shape indicated that the piglets were potentially more suitable than adult rabbits for the development of a calibration curve (6). At a young age, this breed of swine contains more fat and water, and has a lower mineral content than other nonobese contemporary swine (7). In these respects, the composition of Hanford miniature piglets closely resembles that of human infants (6). Calibration curves relating TOBEC measurements to FFM and TBW (determined by chemical analysis) were derived for Hanford miniature piglets in the weight range of approximately 2 to 6 kg (6).

The objective of our study was to evaluate whether the derived calibration curves were appropriate for determining the FFM and TBW of human infants from TOBEC measurements. Thus, it was necessary to establish first that the geometry of the infants' and piglets' FFM was comparable. We then used the calibration curves to estimate the FFM, fat, and TBW of healthy infants from their TOBEC measurements. These results were compared with body composition data of similar aged reference infants (8).

MATERIALS AND METHODS

Design. Thirty-four, healthy infants, 2 to 12 wk of age were enrolled. Weight, recumbent length, multiple circumferences, SFT, and limb measurements were obtained at single time points. Following a feed, TOBEC measurements were made on each child. The infants were studied as outpatients, and all measure-

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Correspondence Marta L. Fiorotto, Ph.D., Children's Nutrition Research Center, 6608 Fannin, Suite 601, Houston, TX 77030.

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ments were completed within 1½ h. Subject selection was restricted to infants who were born at term, appropriate for gestational age, with no medical problems, and who received no medication at the time of the study. No dietary criteria were applied in subject selection. The protocol and consent forms were reviewed and approved by the Institutional Review Boards for Human Research for Baylor College of Medicine and Texas Children's Hospital.

Subjects. Eight infants were studied at approximately 2 wk of age (14 to 18 days old), 10 at 4 wk of age (28 to 33 days old), eight at 8 wk of age (53 to 59 days old), and eight at 12 wk of age (83 to 86 days old); there were equal numbers of boys and girls in each group.

Anthropometric measurements. Each infant was weighed naked on an electronic scale (Sartorius 3804 MP; precision ± 0.05 g) at least 3 h after a feed; body weight was determined from the average of 20 measurements. Crown-heel length was measured on a recumbent infant board with a sliding footboard (Perspective Enterprises, Model PE-RILB-122). The following circumferences were obtained using a plastic tape measure (7 mm in width): head (frontooccipital), chest (at the level of the nipples with the infant recumbent), abdominal (at the navel), midupper arm, and midthigh. Triceps, biceps, subscapular, suprailiac, and thigh SFT measurements were made as described by McGowan *et al.* (9) using Lange calipers. All measurements were made on the left side of the body by the same observer, and each anthropometric determination was the mean of three measurements.

TOBEC measurements. Before measurement in the TOBEC instrument, each infant was fed and allowed to become drowsy (no change in TOBEC signal was detected when a 4-wk-old infant was measured both before and after consuming 128 g of formula). The infant was dressed (with arms and legs covered) and swaddled to ensure that both arms and legs remained parallel with the main axis of the body and that their movement was restricted. TOBEC measurements were made in a modified EMME M-60 instrument (DICKEY-john, Auburn, IL) as previously described (4–6). The infant was placed supine on the instrument sled in a position that corresponded to that in which the piglet measurements had been obtained (6). Ten 1-s readings, each preceded and followed by a background measurement, were recorded over a 5- to 10-min period, and an average value (TOBEC #) was derived; if the infant moved or cried during the measurement, the reading was disregarded. The infant was encouraged to suck on a pacifier during the procedure. As previously discussed, the TOBEC technique does not place the infant at any risk (4). No complications occurred during or subsequent to the study.

A standard, consisting of a wire loop in series with a resistor, was measured daily to monitor instrument stability and to derive a correction factor that standardized all infant measurements to those of the miniature piglets used to construct the calibration curves.

Calculations. The weight of FFM and the volume of TBW were calculated for each infant using the calibration curves derived from Hanford miniature piglets (6).

$$\text{FFM (kg)} = 0.0448\,[\sqrt{(\text{TOBEC}\ \#\cdot L_c)}] - 0.693 \qquad 1)$$

$$\text{TBW (l)} = 0.0349\,[\sqrt{(\text{TOBEC}\ \#\cdot L_c)}] - 0.490 \qquad 2)$$

where TOBEC # is the corrected mean for the infant, and L_c is the length of the "conductive" bulk of the infant's body, *i.e.* crown-heel length minus head diameter (calculated from the head circumference). Total body fat was calculated as the difference between body weight and FFM.

Midupper arm muscle circumference and area were calculated from the midupper arm circumference and triceps SFT; similarly, values were calculated for the thigh muscle circumference and area (10). Estimates of the circumference and area of the lean trunk also were computed using chest circumference and subscapular SFT.

Statistical analysis. Values are expressed as mean ± SD. Correlations and linear relationships were tested by regression analysis. Adjustments for age and gender were done by analysis of covariance (11).

RESULTS

Infant characteristics. The weights and lengths of each age groups are summarized in Table 1. Boys were on average 0.54 ± 0.12 kg heavier and 1.65 ± 0.49 cm longer than girls. The weights of the 2-wk-old infants ranged from 100 to 120% of their birth weight; the average was 111%.

Anthropometric measurements were incomplete for two of the 4-wk-old infants. Reproducibility of abdominal circumference measurements was poor and the measurements were discontinued. Circumferences and SFT measurements also are summarized in Table 1.

Shape of the FFM. Crown-heel length minus the head diameter was used as the length of the bulk of the infant's FFM and chest circumference was assumed to reflect the average circumference of FFM. To determine whether the geometry of the FFM was similar for infants and piglets, the relationships between length and chest circumference and between length and chest cross-sectional area were examined. Length and chest circumferences were linearly related in infants and piglets and neither the slopes

Table 1. *Anthropometric measurements of infants at 2, 4, 8, and 12 wk of age*

	Age (wk)			
	2 (*n* = 8)	4 (*n* = 10)	8 (*n* = 8)	12 (*n* = 8)
Wt (kg)	3.90 ± 0.27* (3.54–4.39)	4.52 ± 0.43 (3.76–5.06)	5.34 ± 0.80 (4.45–6.91)	5.79 ± 0.73 (4.70–6.54)
Length (cm)	52.9 ± 1.2 (51.3–55.1)	55.5 ± 1.6 (53.0–58.4)	58.1 ± 2.0 (55.0–61.5)	59.3 ± 1.7 (55.8–61.2)
Circumferences (cm)				
Midupper arm	11.3 ± 0.5	12.3 ± 0.7	13.2 ± 1.4	13.5 ± 1.1
Midthigh	16.9 ± 0.9	17.4 ± 0.9†	19.5 ± 1.5	20.6 ± 1.8
Chest	35.3 ± 0.7	36.7 ± 1.5	39.5 ± 2.3	40.2 ± 2.0
Skinfolds (mm)				
Biceps	4.9 ± 0.8	4.9 ± 0.7	5.6 ± 1.0	5.6 ± 0.6
Triceps	6.0 ± 0.7	7.1 ± 1.4	7.9 ± 1.4	8.3 ± 1.5
Subscapular	6.3 ± 0.7	6.5 ± 1.1	7.9 ± 1.6	6.9 ± 1.6
Suprailiac	6.4 ± 1.5	7.3 ± 1.9	10.2 ± 2.7	9.1 ± 3.4
Thigh	10.6 ± 2.0	12.4 ± 2.8	14.7 ± 1.9	18.1 ± 3.7

* Mean ± SD; (range).

† *n* = 8.

(0.90 *versus* 0.86, respectively) nor the intercepts (−1.98 *versus* 0.67, respectively) of the regressions for infants and piglets were significantly different from one another. Similar results were obtained for the relationships of length to chest cross-sectional area. These data suggest that the FFM of infants and piglets are of similar shape.

FFM. The mean FFM (derived from equation 1) for each group of infants is presented in Table 2. Boys had a larger FFM than girls of the same age (0.34 ± 0.08 kg; $p < 0.001$). Because the gender effect was still evident after adjustments had been made for both age and body weight (0.13 ± 0.06 kg; $p < 0.05$) or length (0.09 ± 0.04 kg; $p < 0.05$), the disparity could not be explained simply by the difference in the body weight or length of boys and girls of the same age.

FFM was correlated with recumbent length and body weight ($r = 0.97$ and 0.94, respectively); together, length and weight accounted for 96.4% of the variability in FFM

[FFM (kg) = 0.12 length (cm) + 0.17 weight (kg) − 3.35].

Estimates of FFM were correlated with arm muscle circumference ($r = 0.82, p < 0.001$), thigh muscle circumference ($r = 0.73$, $p < 0.001$), and the circumference of the lean trunk ($r = 0.87$, $p < 0.001$). Correlations with corresponding cross-sectional areas were identical. The highest multiple correlation was obtained when arm and trunk measurements were both regressed against FFM ($r = 0.91, p < 0.001$). Within each age group, the correlations with arm and thigh muscle circumferences were weakest in the youngest infants and increased with age. The strength of the correlation with the lean trunk measurement, however, was fairly constant for each age group.

Total body fat. Total fat content and fat content as a percent of body weight are shown in Table 2. The percent of fat, on average, increased with age but the range of values within each age group was considerable. Analysis of the factors contributing to the variance in fat, identified not only weight and age, but also gender as determinants of an infant's fat content; after controlling for age and weight, the girls, on average, had 0.13 ± 0.06 kg more fat than boys ($p < 0.05$).

The percent of fat in the body correlated with all the measured SFT, the weakest correlation occurred with the biceps SFT ($r = 0.52, p < 0.001$) and the strongest with the thigh SFT ($r = 0.82$, $p < 0.001$). The thigh SFT was significantly higher in girls than boys after accounting for differences in body weight ($p < 0.05$); this association was not age dependent. The best predictors of total fat content were thigh SFT, suprailiac SFT, and gender which together accounted for 96% of the variability in fat content. Correlations between fat content and SFT were not improved by using a logarithmic transformation of the SFT data.

TBW. The TBW of infants was calculated from their TOBEC measurements (equation 2). Absolute values and the relative concentrations in the whole body or FFM are presented in Table 2. The relative amount of water in the body decreased with age reflecting both the increase in fat content and a slight decrease in FFM water content with age. TBW was correlated with both length and body weight ($r = 0.98$ and 0.94, respectively); when combined, length and weight predicted 97% of the variability in TBW [TBW (l) = 0.09 length (cm) + 0.13 weight (kg) − 2.65]. No gender effect could be identified.

DISCUSSION

Little is known about the body composition of normal infants from birth through early childhood due to the limitations of existing methodologies. We believed that the TOBEC methodology was suitable for estimating the FFM of infants, in that the measurements were precise, rapid, safe, and noninvasive (5). Using Hanford miniature piglets, calibration curves were derived to translate TOBEC readings into estimates of FFM and TBW (6). To determine whether the derived calibration curves were applicable to human infants, we first had to establish the comparability of the geometry and composition of the infant and the piglet.

To estimate the weight of FFM or the volume of TBW required transformation of the TOBEC signal to $\sqrt{(\mathrm{TOBEC}\ \# \cdot L_c)}$, where the length is that of the conductive bulk of the body (6). The main components of the head, *i.e.* bone and brain tissue, have conductive and dielectric properties at 5 MHz that are similar to those of fat (4, 12–14), and therefore, interact minimally with the instrument's magnetic field. Because the head constitutes a much larger portion of the infant's length than of the piglet's, substantial error would result if whole body lengths were used. The lengths selected for infants and piglets were considered to reflect the portions of their bodies with comparable dielectric and conductive properties and to represent the lengths of the bulks of their FFM.

The calibration curves are defined in part by the shape of the cross-sectional area over the length of FFM. To determine whether the shape of the infant and piglet FFM were analogous, the relationships between chest circumferences and FFM lengths were compared and found to be similar for the two species. Chest and abdominal circumferences were similar and tracked closely in those infants in whom both circumferences were measured, as well as in the piglets (6). Thus, the described relationship between length and circumference should also pertain to the

Table 2. *TOBEC determinations of the FFM, fat, and water content of infants at 2, 4, 8, and 12 wk of age*

	Age (wk)			
	2 ($n = 8$)	4 ($n = 10$)	8 ($n = 8$)	12 ($n = 8$)
FFM* (kg)	3.38 ± 0.26† (3.11–3.86)	3.82 ± 0.22 (3.51–4.22)	4.25 ± 0.39 (3.80–4.84)	4.44 ± 0.31 (3.90–4.87)
Fat (kg)	0.52–0.11 (0.35–0.69)	0.70 ± 0.31 (0.24–1.19)	1.09 ± 0.45 (0.65–1.92)	1.35 ± 0.49 (0.80–2.31)
Fat (% BW)‡	13.2 ± 2.7 (9.8–18.1)	15.1 ± 5.6 (7.3–23.4)	19.8 ± 5.3 (13.7–28.3)	22.8 ± 5.5 (15.9–33.5)
Water§ (liter)	2.69 ± 0.20 (2.47–3.05)	3.03 ± 0.17 (2.79–3.34)	3.36 ± 0.30 (3.01–3.82)	3.51 ± 0.24 (3.09–3.85)
Water (% BW)	68.9 ± 2.1 (65.1–71.7)	67.3 ± 4.5 (60.6–74.3)	63.4 ± 4.2 (56.6–68.3)	61.0 ± 4.4 (52.5–66.4)
Water (% FFM)	79.4 ± 0.1 (79.2–79.5)	79.2 ± 0.1 (79.0–79.3)	79.1 ± 0.1 (78.9–79.2)	79.0 ± 0.1 (78.9–79.2)

* Calculated from equation 1.

† Mean ± SD; (range).

‡ Body wt.

§ Calculated from equation 2.

trunk, which for both the infants and piglets represented the bulk of the FFM. Moreover, the shape of the infant's cross-sectional area in the supine position is marginally flattened in the anterior-posterior axis. This shape is similar to that of the piglet lying in the lateral recumbent position in which the TOBEC measurements had been made for calibration purposes. These comparisons suggest that the geometry of the bulk of the conductive tissues, as "seen" by the instrument, is not grossly different between the calibration model and the infant subjects, provided appropriate care is taken to position the subjects and minimize their movements.

Similarity in the chemical composition of the infant and the piglet improves the predictive accuracy of the calibration from two standpoints. First, the transformed signal, $\sqrt{(\text{TOBEC} \# \cdot L_c)}$ predicts the volume of the conductive tissue (6). The densities of the FFM of infants between birth and 3 months of age and of piglets of comparable size, however, are equivalent [1.063 to 1.065 ml/g FFM (8) *versus* 1.059 to 1.064 ml/g FFM (6), respectively] and reflect similar proportions of protein, water, and mineral in their FFM. Thus, the weights of the infants' FFM were calculated directly from the piglet calibration curve. Second, nonconductive fat and cortical bone interspersed within the FFM, alter the interaction with the electromagnetic field (6). This effect is accounted for by the calibration curve provided the proportions of internal fat and bone in piglets and infants are similar. A comparison of body composition data for young piglets (6, 15) with the limited data for human infants (9, 16) suggests that these variables are likely to be comparable for the two species at parallel developmental ages. Variations in the water and electrolyte concentrations of the FFM within physiological limits appear to have a minimal effect on the relationship between the transformed TOBEC signal and the weight of FFM or TBW and will not compromise the predictive accuracy of the calibration curves (6). The above analysis of the determinants of the calibration curves' predictive accuracy indicates that the degree of similarity in the geometry of the FFM of the species used for calibration and the infants will represent the main source of error. The miniature piglets appear to be appropriate in this regard, and therefore, the calibration curves developed for the piglets should also be appropriate for predicting the body composition of normal infants.

Absolute validation of the derived calibration curves, and hence the absolute accuracy of TOBEC-derived body composition measurements, ultimately requires comparison with direct measurements of body composition. Because such measurements can be made only in animals, studies of human infants have relied on indirect techniques such as those adopted by Fomon *et al.* (8) to derive the body composition of reference infants from birth to 6 months of age. Although, the approach is not ideal given the uncertainty in many of the assumptions made and the large error associated with the measurements of TBW and K in young subjects (17, 18), there are no alternatives at this time. The background characteristics of the group of infants in our study were similar to those of the reference infants. Therefore, we have compared our data for the 4-, 8-, and 12-wk-old subjects with descriptions of the 1-, 2-, and 3-month-old reference infants. The body composition of 2-wk-old infants was assumed to be intermediate between that at birth and 1 month of age. The minimal uncertainty associated with the TOBEC-derived estimates of FFM, fat, and TBW can be determined directly from the piglet measurements and assumes that no further error was introduced in the extrapolation from piglets to infants. The SEE for the FFM (and thus for fat also) and TBW calibration curves were 70 g and 50 ml, respectively; the corresponding 95% prediction intervals for individual measurements (approximately 2 SEE) were 160 g and 120 ml, respectively. These uncertainties are lower than those associated with TBW measurements by isotope dilution (17), and FFM estimated from total body K (18). The magnitude of the uncertainty of the TOBEC method, however, is still such that the technique is better suited to studies that estimate the average body composition of groups of subjects rather than of individuals.

The fat contents derived from TOBEC measurements of the 4-, 8-, and 12-wk-old infants in our study were the same as values reported for the reference boy at 1 (15.1%), 2 (19.9%), and 3 months of age (23.2%), respectively. The fat content values of the 2-wk-old infants were compared with their fat content values at birth computed using the equation derived by Brans *et al.* (19) in which birth weight is related to body fat content measured by chemical analysis. On average, the infants were 12.7% fat at birth. Thus, fat content may have increased marginally over the first 2 wk of life, commensurate with changes in body weight. These fat values, however, were higher than those reported by Spady *et al.* (20) for newborn infants in whom lean body mass was determined from total body K measurements.

The TOBEC-derived estimates for TBW (as a percent of body weight) up to 12 wk of age were comparable to the corrected values for deuterium space reported for infants of similar ages (8, 21, 22), but lower than estimates for TBW determined by the dilution of $H_2{}^{18}O$ (5). The age-associated decrease in TBW largely reflected the relative increase in fat content, because the change in the water content of the FFM was small. The latter values were marginally lower than those of the reference infant (8), and reflected the relative hydration of the FFM of young piglets with a FFM of equivalent size. However, this difference is insignificant given the large uncertainty associated with TBW estimations by isotope dilution (17). Thus, TOBEC measurements can be used in conjunction with the described calibration to determine the TBW of healthy infants within the age range studied.

The values for TOBEC-derived FFM and fat also correlated with anthropometric indices of these body compartments. FFM was found to track closely the circumferences or areas of the arms, trunk, and thigh. Because the musculature of the limbs is relatively underdeveloped in the young infant, the lean component of the trunk constitutes the largest fraction of the FFM. Indeed, this parameter had the highest correlation with total FFM, and the relationships with the limb measurements improved with age. The estimated values for total body fat reflected the changes in SFT, especially for the suprailiac and thigh sites. Our findings were consistent with those of McGowan *et al.* (9) who showed that these two SFT are more sensitive than others to the subject's adiposity and can be measured more reliably than other SFT in newborn infants. TOBEC measurements, therefore, are at least as sensitive as anthropometric measurements to changes in lean body mass and adiposity, although the greater precision of TOBEC measurements offer a distinct advantage over standard anthropometric measurements.

According to the present evaluation, therefore, the TOBEC technique, with the appropriate calibration curves, appears to quantitate fat, FFM, and TBW with at least the precision of alternative techniques currently used for the infant population. The close parallel between the body composition of infants estimated from the TOBEC measurements and the composition of reference infants suggested that the method used to calibrate this instrument was appropriate for normal infants. The accuracy of the calibration potentially can be improved by more precisely accounting for differences in the geometry of the FFM of individual infants and the piglets, as was accomplished when using the technique to determine the FFM and TBW of piglets themselves (6). It is evident, however, that the absolute accuracy of the method will be established only if techniques are developed that can measure more directly the mass of fat and lean tissues in healthy infants. Nevertheless, because of the high precision of the TOBEC measurements, the technique lends itself especially well to longitudinal studies, such as balance studies, that require repeated measurements on the same subject.

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