Predicting body composition from anthropometry and bioimpedance in marginally undernourished adolescents and young adults[1–3]

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ABSTRACT Body-composition prediction equations were developed using data from a sample of 201 female and male Guatemalan ladinos (ie, people of Amerindian-European descent) aged 11–25 y. Fat-free mass (FFM) values were estimated from body density by using the two-component model and age- and sex-specific values for the density of FFM. The root-mean-square error (RMSE) of the best model predicting FFM from a set of simple anthropometric variables was 1.59 kg for females and 1.90 kg for males. The addition of more extensive anthropometry to the set of candidate predictors reduced the RMSE to 1.42 kg for females and 1.88 kg for males. The subsequent addition of a bioelectrical impedance measure (Ht^2/R) further reduced the RMSE to 1.32 kg for females and 1.82 kg for males. These results suggest that for a marginally undernourished population with relatively little body fat, simple anthropometrics are as useful as more sophisticated measures for the prediction of body composition. *Am J Clin Nutr* 1992;55:1051–9.

KEY WORDS Fat-free mass, body composition, anthropometry, undernutrition, adolescents

Introduction

The assessment of body composition in developing countries is usually made under field conditions and is limited to simple techniques such as anthropometry. Many equations have been developed for the prediction of body composition using common anthropometric measurements, but these equations are population-specific and have rarely been cross-validated on groups of different ethnic background, nutritional status, or nutritional history. In particular, the body-composition equations available for children and adolescents are based on well-nourished populations of European origin with physical characteristics distinct from those of marginally undernourished populations of the developing world. Patterns of fat distribution as measured by skinfold thickness have been shown to differ across ethnic groups and across degrees of undernutrition (1, 2). Furthermore, the equations commonly used for children and adolescents (3, 4) are based on estimates of body fatness derived from the two-component model of hydrodensitometry, which assumes a constant (usually adult) value for the density of the fat-free mass (FFM). It is now well established that chemical maturity is not reached until early adulthood (5, 6) and that the use of adult values for the density of the FFM in the two-component model results in systematic overestimates of body fatness in adolescents (5). In the past few years prediction equations for adolescents based on more direct measures of the composition of the FFM (7) or on age- and sex-specific constants for the density of the FFM (8) have been published, but these have not been cross-validated on a population showing current or past undernutrition.

The primary objective of this study was to derive body-composition prediction equations that could be applied to a population of economically disadvantaged adolescents and young adult ladinos (ie, people of Amerindian-European descent) living in rural Guatemala. These young people were participants in a food-supplementation program as children in the early and mid-1970s (9) and were the subjects of a recent follow-up study designed to assess the long-term impact of supplementation on growth and development. Both studies were conducted by the Instituto de Nutricion de Centro America y Panama (INCAP) in Guatemala City. Extensive anthropometry was obtained on all subjects in the follow-up study for the assessment of body composition. In a subsample selected to participate in a work-capacity test, measures were also obtained of the two most variable components of FFM during adolescence: water (bioelectrical impedance) and bone mineral (photon absorptiometry). These anthropometric, bioimpedance, and photon absorptiometry measurements determined the set of candidate predictors from which the prediction equations were derived.

It was recognized that many researchers working with marginally undernourished populations in Latin America have available only a few anthropometric variables and would not be able to use equations built from an extensive set of candidate predictors. Thus, to meet the needs of researchers working with limited anthropometry as well as to achieve the high precision

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TABLE 1
Candidate predictors included in the three full models

Model 1	Model 2	Model 3
Age	Variables in model 1	Variables in model 2
Weight	Suprailiac skinfold thickness	Ht^2/resistance
Height	Subscapular skinfold thickness	Bone mineral content
Wt/ht^2	Calf skinfold thickness	
Triceps skinfold thickness	Biacromial diameter	
Arm circumference	Biilial diameter	
Arm-muscle area	Knee diameter	
Arm-fat area	Abdominal circumference	
	Calf circumference	

possible with extensive anthropometry and technology, a prediction equation was developed from each of the following pools of candidate predictors: *1*) limited anthropometry available in most existing data sets, *2*) extensive anthropometry, and *3*) extensive anthropometry plus bioimpedance and photon absorptiometric measures.

A second objective was to cross-validate three published equations that were developed using data from relatively well-nourished adolescent populations from Czechoslovakia (10), Illinois and Arizona (7), and the Fels Longitudinal Study from Ohio (8). The Czechoslovakian (CZ-SL) equation was chosen because it is very commonly used for adolescent populations and because the conversion of predicted body density to percent fat is based on one equation (11) for all age groups. We expected it to yield systematic overestimates of percent fat in our sample, particularly among the younger subjects. The Illinois-Arizona (IL-AZ) and the Fels equations were chosen because their calculated (observed) values of body fatness were adjusted for age trends in the composition of FFM and should be free of the bias introduced when adult constants are applied to chemically immature populations. Of the three equations, we expected the Fels equation to have the lowest error of prediction because it includes a measure of water content (bioelectrical impedance) as a predicting variable.

Methods

Subjects

The sample consisted of 211 male and female ladino Guatemalans aged 11–25 y who were recruited through public schools and vocational training centers serving poor and overcrowded neighborhoods in Guatemala City. Sampling was stratified by sex, age, and triceps skinfold thickness. The four age groups corresponded roughly to the four stages of maturation during adolescence: 11–12 y, prepubescent; 13–15 y, pubescent; 16–18 y, postpubescent; and 19+ y, adult. Stratification by triceps was designed to overrepresent subjects at the extremes of fatness and thus to increase the stability of the regression of body composition on anthropometry. The five triceps groups corresponded to the percentile ranges 0–16th, 17th–33rd, 34th–67th, 68th–84th, and 84th–100th of age- and sex-specific triceps distributions observed in a population of rural ladino Guatemalans surveyed before this study. At least five subjects were chosen for each cell of the $2 \times 4 \times 5$ stratification scheme. Ten of the 211 subjects did not successfully complete the densitometry trial but the stratification scheme was essentially preserved; all cells had at least five subjects, except for three cells, which had four.

Body-composition measures

Body density was determined by hydrostatic weighing with corrections for residual volume and intestinal gas as described by Buskirk (12). Underwater weights were taken after maximum exhalation at least five times and until consecutive measures stabilized to within 50 g. The average of the final three was recorded as the underwater weight. Residual volume was measured by helium dilution with the subject sitting upright and the water at neck level. A validation study of 34 subjects conducted at INCAP showed that this method had a very high correlation (r = 0.996) with the preferred method of measuring residual volume at the time of the hydrostatic weight. Intestinal gas (IG) has been reported to average ≈120 mL (13) in adult subjects. No mean has been reported for children but it is assumed that it would be less than for adults. Although IG introduces very little error into the estimate of body density, we wanted to avoid the potential age and size bias of using one adult mean for all subjects. Thus, IG was scaled to body weight (BW) by the equation

$$IG\ (mL) = 2.0 \times BW\ (kg)$$

Percent fat and FFM were calculated from Siri's equation (14) by using the age- and sex-specific values proposed by Lohman (5) for the density of FFM:

$$\text{Percent fat} = 100 \times \left(\frac{1}{d_b} - \frac{1}{d_{ffm}}\right) \Big/ \left(\frac{1}{d_{fat}} - \frac{1}{d_{ffm}}\right)$$

$$FFM = (1 - \%fat/100) \times BW$$

where d_{ffm} is the density of FFM, d_{fat} is the density of fat (0.9007 g/mL), and d_b is body density. (The specific equations for each age and sex group are presented in Appendix A.) Because of the delayed maturity observed in this population, the appropriate age-specific value was determined by skeletal age as estimated from the left hand-wrist radiograph using the Tanner Whitehouse II method (15). For those older subjects (girls > 16 y and boys > 18 y) who had reached skeletal maturity, chronological age was used to determine the appropriate constant.

Weight on land was measured to the nearest 100 g and height to the nearest 0.1 cm. Skinfold thickness was measured on the right side of the body using a Holtain caliper (Holtain Ltd, Crosswell, Crymmych, Dyfed, Wales) and recorded to the nearest 0.1 mm. Measurements were taken in triplicate and averaged for each of the seven skinfold-thickness sites: triceps, biceps, subscapular, midaxillary, suprailiac, anterior thigh, and medial calf (16). Diameters were measured to the nearest 0.1 cm with a Holtain anthropometer at six body sites: biacromial, biiliac, elbow, wrist, knee, and ankle (17). Body circumferences of the

TABLE 2
Values of variables used in model building*

	Females (n = 76)	Males (n = 79)
Candidate predictors		
Age (y)	15.9 ± 3.6 (9.9–24.7)	15.4 ± 3.3 (9.4–24.1)
Weight (kg)	41.6 ± 8.2 (22.9–63.0)	44.2 ± 12.2 (20.8–70.1)
Height (cm)	148.0 ± 8.7 (122.1–165.6)	152.7 ± 13.3 (120.4–181.3)
Wt/Ht^2 (g/cm^2)	1.88 ± 0.26 (1.34–2.60)	1.86 ± 0.26 (1.39–2.51)
Triceps skinfold thickness (mm)	11.3 ± 3.0 (6.6–18.4)	7.8 ± 2.5 (4.0–15.0)
Subscapular skinfold thickness (mm)	9.9 ± 4.3 (4.0–24.4)	7.1 ± 2.7 (3.6–19.0)
Suprailiac skinfold thickness (mm)	12.7 ± 6.6 (3.9–32.1)	8.6 ± 4.9 (3.6–23.3)
Calf skinfold thickness (mm)	10.3 ± 3.6 (3.7–23.3)	6.2 ± 2.1 (2.7–12.9)
Knee diameter (cm)	8.2 ± 0.4 (7.2–8.8)	8.9 ± 0.7 (7.3–10.3)
Biiliac diameter (cm)	25.3 ± 2.4 (19.3–29.8)	24.4 ± 2.8 (18.9–34.1)
Biacromial diameter (cm)	32.9 ± 2.1 (26.8–36.7)	34.2 ± 3.7 (26.0–41.4)
Arm circumference (cm)	21.8 ± 2.6 (15.9–28.5)	22.4 ± 3.4 (16.0–29.9)
Calf circumference (cm)	29.9 ± 2.7 (23.5–35.4)	30.5 ± 3.6 (22.7–37.4)
Abdominal circumference (cm)	68.1 ± 7.5 (54.8–88.0)	67.7 ± 7.7 (52.7–89.7)
Arm-muscle area (cm^2)†	26.9 ± 5.6 (14.2–41.3)	32.6 ± 10.8 (14.4–58.5)
Arm-fat area (cm^2)‡	11.6 ± 4.0 (5.0–23.3)	8.3 ± 3.1 (3.7–18.0)
Ht^2/resistance (cm^2/Ω)	33.2 ± 5.9 (17.28–42.22)	41.5 ± 12.2 (18.0–75.4)
BMC (g/cm)	0.63 ± 0.11 (0.35–0.80)	0.70 ± 0.21 (0.34–1.39)
Dependent variable		
FFM (kg)	32.7 ± 5.7 (18.5–43.1)	38.1 ± 10.3 (18.4–64.1)
Other variables		
Body density (g/cc)	1.044 ± 0.01 (1.016–1.063)	1.061 ± 0.01 (1.039–1.085)
Percent fat (%BW)	20.8 ± 5.0 (10.5–33.8)	13.6 ± 4.8 (0.8–22.0)
SA-CA (y)§	−0.72 ± 1.15 (−2.7–1.6)	−0.58 ± 1.35 (−3.7–2.9)

* $\bar{x}$ ± SD (range).
† (Arm circumference − 0.314 × triceps skinfold thickness)^2/12.56 (ref 24).
‡ (Arm circumference × triceps skinfold thickness/20) − 3.14 × (triceps skinfold thickness/10)^2/4 (ref 24).
§ Skeletal age–chronological age for females aged < 16 y (n = 43) and males aged < 18 y (n = 62).

arm, waist, thigh, and calf were measured with a flexible steel tape to the nearest 0.1 cm (18). Bioelectrical resistance (R) to a small excitation current of 800 mA at 50 kHz was measured using the RJL impedance analyzer (model BIA-103; RJL Systems, Inc, Detroit). Electrodes were positioned on the dorsal surface of the right hand and foot as described by Lukaski et al (19) with the subject supine and with arms and thighs parted so that there was no skin-to-skin contact. Bone mineral content (BMC) and bone width of the one-third distal radius of the nondominant arm were measured by a Norland Single Beam Bone Densitometer (model 2780; Nordland Corp, Fort Atkinson, WI) according to the protocol described by Cameron and Sorenson (20).

Reliability estimates of all measures were obtained for 9% of the sample. The technical errors of the measurement (21) for anthropometry were within recommended ranges (16–18). The technical error was 18.2 Ω for resistance, 0.012 g/cm for bone mineral content, and 0.00077 g/cc for body density.

This protocol was approved by the Cornell University Committee for Research on Human Subjects and the Research Review Board at INCAP.

Statistical analyses

Dependent variable. A preliminary analysis showed that the mean square errors of models predicting FFM, percent fat, and body density were similar when the predicted values were converted to the same unit of measure—in this case, FFM (kg). Given that bioelectrical-impedance measures are most closely correlated with FFM and that FFM equations have been shown to perform slightly better in cross-validation studies than density equations (22), FFM was chosen to be the dependent variable.

Candidate predictors. As explained in the Introduction, our goal was to develop an equation for each sex from each of three pools of independent variables: *1*) limited anthropometry (model 1), *2*) extensive anthropometry (model 2), and *3*) extensive anthropometry plus bioelectrical impedence and photon-absorptiometric measures (model 3). The candidate predictors for model 1 (**Table 1**) were limited to age, four anthropometric measurements taken easily in the field, and three derived variables that have been shown to be highly correlated with total body fat (and thus with FFM when weight is in the equation): weight/height^2 (wt/ht^2) (23), arm-muscle area, and arm-fat area (24, 25). Model 2 included 16 variables chosen because *1*) they had appeared repeatedly in the literature as good predictors of FFM, *2*) they represented a skinfold thickness, circumference, or diameter from both the torso and limb, or *3*) they had high correlations with FFM controlling for weight. These 16 variables plus ht^2/R and BMC were included in model 3. Resistance was expressed in the form ht^2/R because that is a function of total-body-water volume (19), which is highly correlated with FFM.

Model building. The sample was randomly divided into a model-building subsample (76 females, 79 males) and an internal-validation subsample (22 females, 24 males).

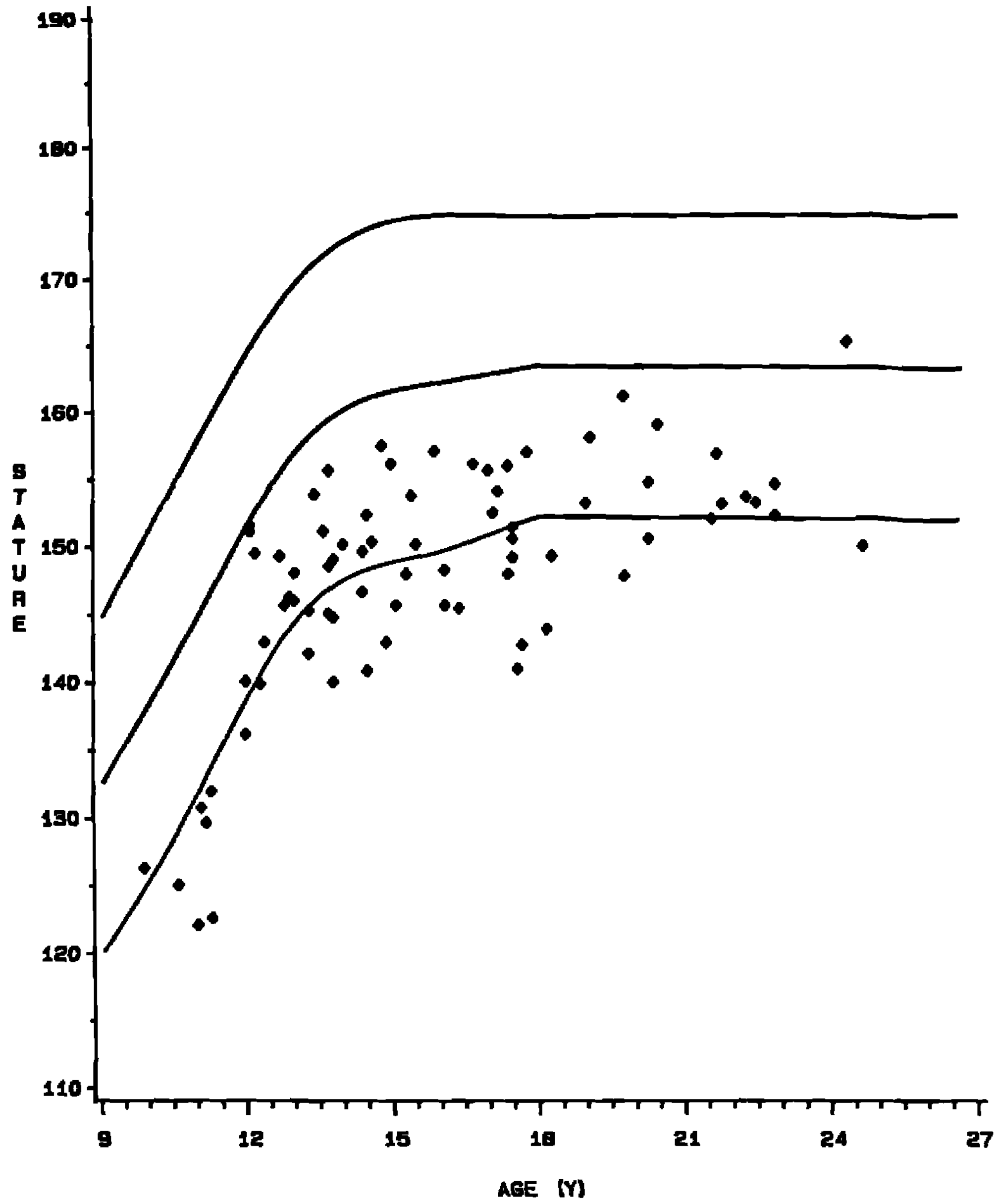

FIG 1. Stature (cm) for age of female subjects compared with the 3rd, 50th, and 97th percentiles of the NCHS reference population (ref 32).

FFM (kg) was regressed on the three models for males and females separately. Two independent criteria were used to select two best models of all possible subsets: the minimum *SBC* (Schwarz Bayesian criterion) statistic (26) and the minimum absolute difference between the C_p statistic and p, the number of regressors in the reduced model (27). The *SBC* statistic is a correction of the Bayesian-based *AIC* (Akaike information criterion) statistic, which has performed well under simulations as a criterion for model selection. Flores (unpublished observations, 1989) developed a body-composition prediction equation for Guatemalan adults and reported that the model chosen by the *SBC* statistic performed better on cross-validations than did those chosen by three other model-selection criteria (including $C_p - p$). The $C_p - p$ criterion was developed by Mallows (28), who advises that there is no one best model but rather a series of good models for which $C_p - p$ is small. Our best model was that with a $|Cp - p| < 0.1$ and with the least number of predictors and the least evidence of collinearity. Collinearity was assessed for the reduced models by the condition number (CN) computed for standardized residuals with the intercept included. Although no specific cutoff has been established, Belsley et al (28) suggest that a CN of 30 indicates probable collinearity in the model. The two best reduced models selected by these two criteria (*SBC* and $C_p - p$) were then compared on the basis of their performance on the validation subsample. The recommended model was that with the lowest root mean square error for the validation sample (RMSE − V)

$$[\text{sum}(FFM_{pred} - FFM_{obs})^2/n - p]^{0.5}$$

In the event of very similar RMSE − Vs, the best model was that with the lowest condition number.

Variable added plots (29) of the reduced models were examined for nonlinear relationships between each predictor and the residual of FFM regressed on the other selected predictors. No nonlinear relationships were observed.

The three body-composition prediction equations described in the Introduction (7, 8, 10) and given in full in Appendix B were then applied to our entire sample of 201 subjects. The percent-fat predictions from the IL-AZ equation and the percent-fat values calculated from predicted body density in the CZ-SL equation were converted to FFM so that the error of prediction could be compared. The RMSE was defined as

$$[\text{sum}(FFM_{pred} - FFM_{obs})^2/n]^{0.5}$$

Results

Descriptive statistics for the model-building sample are given in **Table 2.** Males tended to be taller, heavier, and leaner than females, with mean percent-fat values of 13.5% for males and 20.8% for females. The sample represented the broad range of body fatness (10.5–33.8% for females, 0.8–22.0% for males) intended by the stratified sampling scheme. Chronic undernutrition is evidenced by delays in skeletal maturation averaging 0.7 y for girls and 0.6 y for boys. Plots of height vs age overlayed with the National Center for Health Statistics (NCHS) reference percentiles (31) (**Figs 1 and 2**) indicate considerable stunting in this sample. Only three subjects reached the 50th percentile of height-

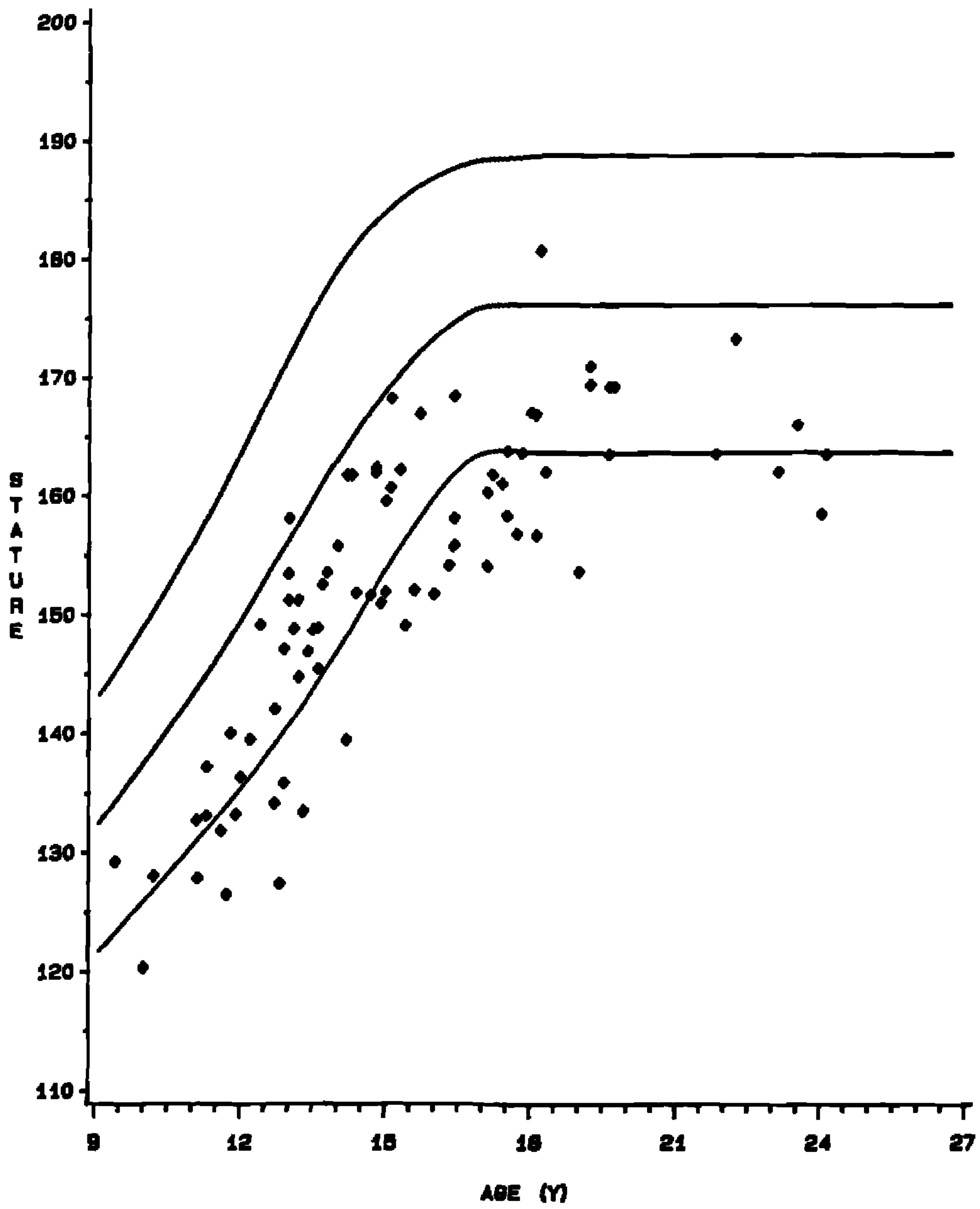

FIG 2. Stature (cm) for age of male subjects compared with the 3rd, 50th, and 97th percentiles of the NCHS reference population (ref 32).

TABLE 3
The best reduced models predicting FFM (kg): females

Model 1			Model 2			Model 3		
RMSE = 1.59 kg R^2 = 0.921 CV = 4.87% CN = 37.6			RMSE = 1.42 kg R^2 = 0.938 CV = 4.34% CN = 85.8			RMSE = 1.32 kg R^2 = 0.946 CV = 4.04% CN = 71.1		
Variable	Regression coefficient	SE	Variable	Regression coefficient	SE	Variable	Regression coefficient	SE
Intercept	10.6566	1.44	Intercept	−1.8883	4.60	Intercept	5.8288	2.28
Weight (kg)	0.8545	0.04	Weight (kg)	0.7018	0.06	Weight (kg)	0.6018	0.06
Wt/ht^2 (g/cm^2)	−6.9209	1.53	Height (cm)	0.1221	0.03	Biilial diameter (cm)	0.2802	0.12
Triceps skinfold thickness (mm)	−0.0411	0.09	Abdominal circumference (cm)	−0.1858	0.05	Abdominal circumference (cm)	−0.1892	0.05
						Ht^2/R (cm^2/Ω)	0.2308	0.06

for-age whereas more than one-third were below the 3rd percentile.

The best reduced models of each of the three full models are given in **Tables 3** and **4**. Weight explains most of the variation in FFM in all models (r^2 = 0.92 for females, r^2 = 0.94 for males). Besides weight, abdominal circumference was retained in reduced model 2 and model 3 for females whereas arm cross-sectional fat area and biilial diameter were retained in two of the three reduced models for males. The addition of more extensive anthropometry to the set of candidate predictors reduced the RMSE by 0.17 kg for females and 0.02 for males. Ht^2/R contributed significantly to the prediction of FFM for both sexes but bone mineral content did not. Including ht^2/R in the model reduced the RMSE by 0.10 and 0.06 kg for females and males, respectively.

The RMSE of each of the three reduced models applied to the internal validation subsample (RMSE-V) was higher than the RMSE for the corresponding model for females but slightly lower for males (**Table 5**). The residuals of FFM from model 1 plotted against age for both the model-building and the cross-validation subsamples (**Figs 3** and **4**) are similar across the 10–25-y age range.

The RMSEs of the CZ-SL, Fels, and IL-AZ equations applied to the 201 subjects in our study are low and strikingly similar (**Table 6**). The plots of the residual of FFM vs age for the CZ-SL equations for males and females and for the Fels equation for males indicate that there are systematic underestimates of FFM in the younger subjects (**Figs 5 and 6**).

Discussion

This study has shown that the body composition of marginally undernourished individuals can be predicted with a high degree of accuracy from a few simple anthropometric variables and that the addition of more extensive anthropometry and sophisticated body-composition measures to the list of candidate predictors does not greatly improve the prediction. The validity and usefulness of the recommended equations will be discussed in light of the following: *1*) the accuracy of our estimates of FFM from hydrodensitometry, *2*) statistical considerations in modeling body composition, and *3*) the representativeness by this sample of marginally undernourished populations in Latin America.

Our estimates of FFM were based on body-density measurements and assumed values for the density of the FFM. These values were the means reported for 2–3-y age groups for both sexes in a well-nourished US sample (5). Although some random error is introduced when group means are applied to individuals, it is less problematic than the systematic error introduced when

TABLE 4
The best reduced models predicting FFM (kg): males

Model 1			Model 2			Model 3		
RMSE = 1.90 kg R^2 = 0.966 CV = 4.98% CN = 9.3			RMSE = 1.88 kg R^2 = 0.967 CV = 4.92% CN = 38.9			RMSE = 1.82 kg R^2 = 0.969 CV = 4.76% CN = 52.8		
Variable	Regression coefficient	SE	Variable	Regression coefficient	SE	Variable	Regression coefficient	SE
Intercept	2.8789	0.83	Intercept	−0.8029	2.35	Intercept	2.0635	0.77
Weight (kg)	0.8736	0.02	Weight (kg)	0.8282	0.03	Weight (kg)	0.7074	0.09
Arm-fat area (cm^2)	−0.4110	0.08	Biilial diameter (cm)	0.2241	0.13	Suprailiac skinfold thickness (mm)	−0.1944	0.07
			Arm-fat area (cm^2)	−0.3835	0.08	Ht^2/R (cm^2/Ω)	0.1554	0.08

TABLE 5
Validation of the three best equations on the internal cross-validation subsample

	Females (n = 22)		Males (n = 24)	
Equation	RMSE-V	CV	RMSE-V	CV
Model 1	1.82 kg	5.44%	1.64 kg	4.30%
Model 2	1.75 kg	5.33%	1.63 kg	4.27%
Model 3	1.64 kg	5.02%	1.59 kg	4.17%

an adult male value is used for all ages and both sexes. Of greater concern is whether the reported age- and sex-specific means apply to a chronically undernourished population of different ethnic background. The hydration of the FFM has been shown to increase during severe undernutrition (32) but it has not been adequately studied in mild to moderate undernutrition. Studies that have examined body composition in moderately undernourished individuals have used conversion constants based on well-nourished populations, at least at some point in the analysis. The more informative of these have estimates of total body water (TBW) from dilution techniques and FFM from hydrodensitometry (using established constants for the density of the FFM). Holmes et al (33) found no significant difference in the hydration of the FFM between groups of West African men of poor and adequate nutritional status. Viteri (34) reported TBW and FFM values for a sample of Guatemalan agricultural workers of differing nutritional status. Our crude calculations of the water content of the FFM using the reported group means for TBW and FFM suggest that FFM hydration increases slightly with declining nutritional status. However, the circular process of using FFM values that are based on assumptions of a constant composition of the FFM to detect differences in the water composition of the FFM necessarily results in an exageration of any true difference. Thus, any difference due to nutritional status is probably small. To our knowledge there are no studies that have investigated the second most variable component of the FFM, bone mineral, in moderately undernourished populations. We did consider that the observed delays in skeletal maturity were probably associated with delays in chemical maturity in general. Using skeletal age to determine the appropriate age-specific constant not only adjusted for these delays, it reduced the variation in chemical maturity associated with a given chronological age.

The high R^2s and the low RMSEs of our equations are not necessarily indicative of large improvements over existing equations. R^2s > 0.98 are typical of models using FFM as the dependent variable and weight as the primary independent variable. Despite the lower R^2 of models predicting body density (0.8–0.9) and percent fat (0.7–0.8), these models are shown to perform similarly to those predicting FFM when the RMSEs are reported in like units. The RMSE and CV of our recommended equations were lower than those reported by Guo et al (8) for the Fels equation, which also used FFM as the dependent variable (2.23 kg and 5.8% for females and 2.31 kg and 5.02% for males). This is probably due to the relative leanness and small body size of our sample rather than to any improvements in methodology. The Fels sample included more obese subjects (particularly females), who are likely to have large errors of prediction. This may also explain why the CVs for our equations for females are much lower than those for the Fels equation, whereas there is little difference in CVs for males.

The RMSE of model 1 was only slightly reduced when the pool of candidate predictors was expanded to include more extensive anthropometry and more sophisticated measures of body composition. Again, this may be due to the relative leanness and homogeneity of our sample. Although sampling was stratified to represent the range of fatness observed in a poor rural Guatemalan population surveyed before this study, that range is considerably less than that observed in US populations. Thus, regressing FFM on weight and height alone produces a RMSE of 1.55 kg for females, whereas the addition of a circumference, a diameter, and Ht^2/R reduces the RMSE to only 1.32 kg. (We cannot recommend this simple weight-and-height equation because it is certain to produce systematic overestimates of FFM in fat people and vice versa.) Furthermore, bone mineral, with its high correlation with weight (0.83 in females, 0.93 in males), was not a significant predictor of FFM in either females or males. This suggests that for a marginally undernourished population

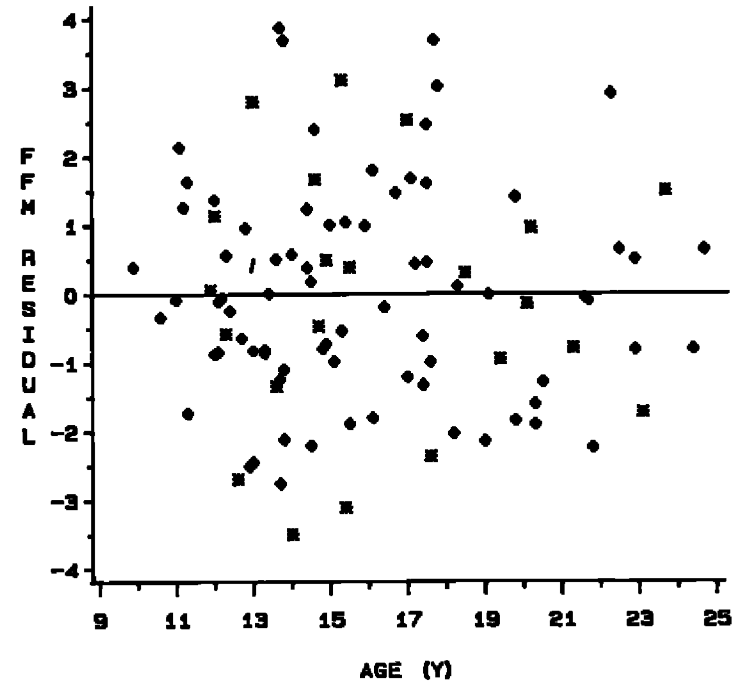

FIG 3. Residuals of fat-free mass (FFM) (predicted minus observed) vs age for females. FFM predictions are from model 1. ◊, model-building subsample; *, internal cross-validation subsample.

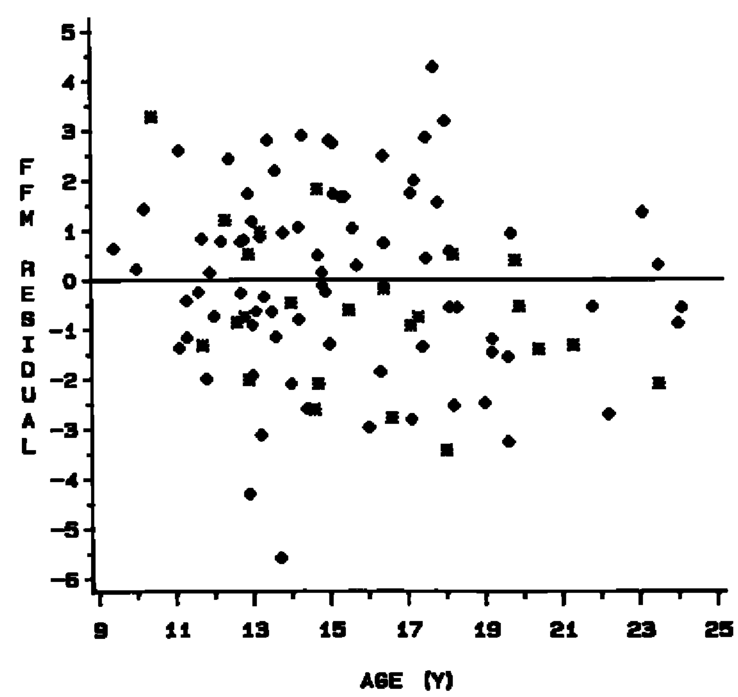

FIG 4. Residuals of FFM (predicted minus observed) vs age for males. FFM predictions are from model 1. ◊, model-building subsample; *, internal cross-validation subsample.

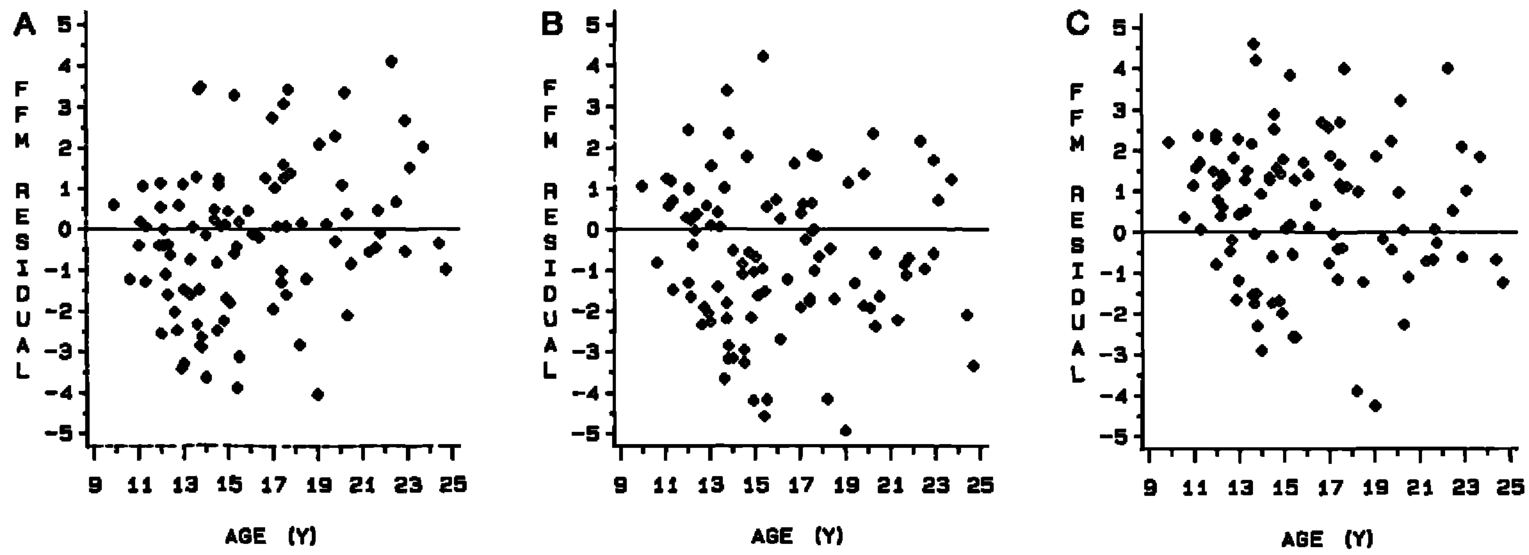

FIG 5. Cross validation of the CZ-SL, Fels, and IL-AZ equations on our sample of females. A—CZ-SL equation (RMSE = 1.80 kg); B—Fels equation (RMSE = 1.82 kg); C—IL-AZ equation (RMSE = 1.84 kg).

with relatively little body fat, simple anthropometry is as useful as more sophisticated measures of body composition for predicting FFM. Measures of bone mineral content and bioimpedance may hold more promise for improving the estimate of FFM using the four-component model than for improving the prediction of FFM in the subsequent regression analysis.

The CZ-SL, Fels, and IL-AZ equations had relatively low RMSEs when applied to our sample. Despite the many differences among these three equations (eg, sample population, predictor variables, units and method of estimating the dependent variable), their RMSEs were strikingly similar. The bioelectrical impedance measures in the Fels equations did not reduce the RMSEs below those of the CZ-SL or the IL-AZ equations, just as bioimpedance did not greatly improve the prediction of FFM from anthropometry in our set of equations. We did observe the underestimates of FFM (overestimates of percent fat) among our smaller and younger subjects that were expected from the CZ-SL equations. Although these errors do not appear to be large, they would produce biased group means for younger subjects. This does not appear to be a function of the ethnic and nutritional differences between the CZ-SL sample and ours but rather of the equation used to calculate percent fat in the young CZ-SL subjects. In fact, the predictions from these three equations suggest that the anthropometry–total body fat relationships observed in well-nourished European populations apply fairly well to a marginally undernourished population. Although our equations have lower errors of prediction, the three equations cross-validated on our sample gave surprisingly good estimates of body composition.

One reason that body-composition prediction equations are population specific is the high degree of collinearity in the models. This produces regression coefficients that are very sensitive to the unique collinearity condition of the observations used in model building. Although the predictions for any model-building sample are unbiased, the coefficients are unstable and the model performs poorly on independent samples that are likely to have slightly different collinearity conditions. Several indices have been devised to quantify the degree of collinearity of a regression model. The variance-inflation factor reported in recent body-composition papers can detect overall collinearity in the model but it is unable to distinguish among several coexisting near dependencies. Belsley et al (28) proposed a double condition for assessing harmful collinearity on the basis of the condition number and variance-decomposition proportions. By their criteria, the equations from models 2 and 3 (Table 3) for females have one or more near dependencies, suggesting that they may not perform well on an independent sample. We are unaware of an independent sample of marginally undernourished adolescents and young adults for whom anthropometry and underwater weights are available, and thus we were unable to assess

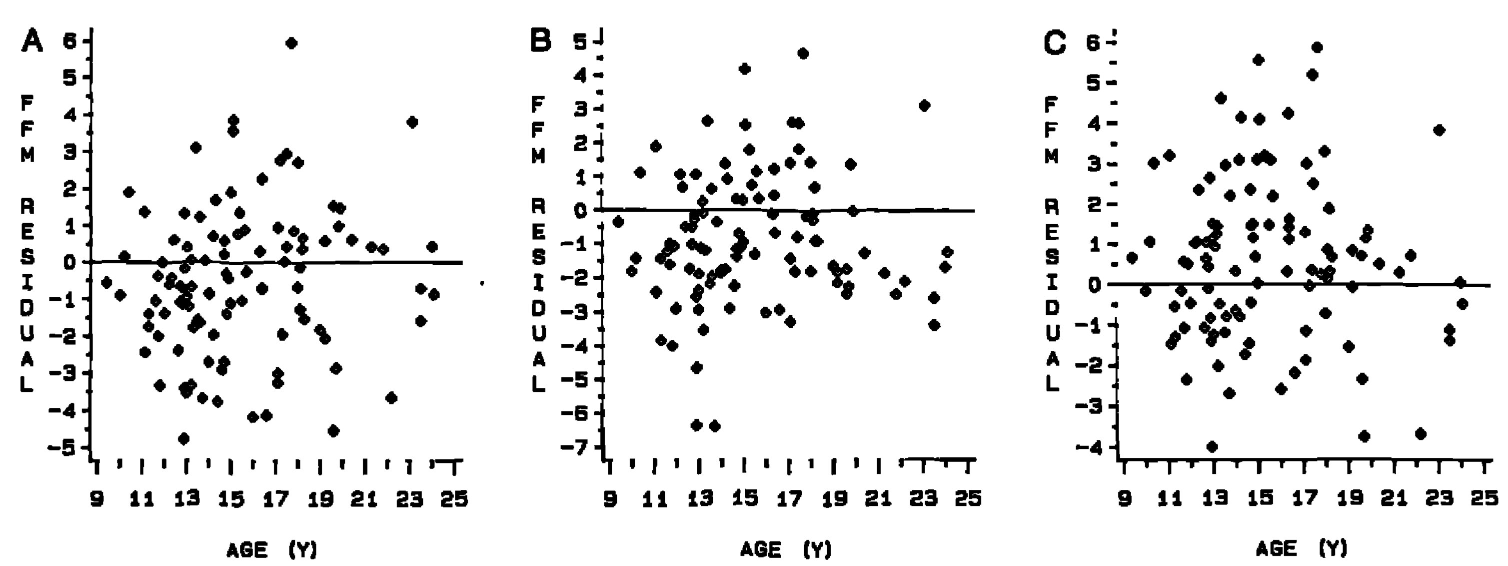

FIG 6. Cross validation of the CZ-SL, Fels, and IL-AZ equations on our sample of males. A—CZ-SL equation (RMSE = 2.05 kg); B—Fels equation (RMSE = 2.07 kg); C—IL-AZ equation (RMSE = 2.11 kg).

TABLE 6
Cross-validation of three published equations on the total Guatemalan sample

	Females (n = 98)		Males (n = 103)	
Equation	RMSE-V	CV	RMSE-V	CV
CZ-SL	1.80 kg	5.51%	2.05 kg	5.37%
Fels	1.82 kg	5.57%	2.07 kg	5.43%
IL-AZ	1.84 kg	5.63%	2.11 kg	5.53%

the external validity of our models. We can only say that the RMSEs of the models applied to the validation subsample for our population were low and do not indicate biases in the prediction of FFM.

Our subjects were recruited through public schools and vocational-training centers serving poor and overcrowded neighborhoods in Guatemala City. The low percentiles for height-for-age (Figs 1 and 2) and the delays in skeletal maturity (Table 2) indicate considerable stunting and delay of maturation, probably due to chronic undernutrition. It is the authors' opinion that this sample better reflects the physical characteristics of poor, undernourished children in Latin America than do the samples used to produce the existing equations. As with any prediction equation, these may not perform well outside the range of the data. We included the height-for-age plots (Figs 1 and 2) and the ranges for many of the variables (Table 2) so that researchers interested in using our equations can check the similarity of their sample to ours. (Space limitations prevent us from giving age-specific ranges.) We look forward to the opportunity to cross-validate these equations on a similar sample for which body density and anthropometry are available.

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APPENDIX A

Calculation of percent fat using age- and sex-specific values for the density of the FFM: percent fat = $[(k_1/D_b) - k_2] \times 100$*

Age	Females			Males		
	D_{ffm}	k_1	k_2	D_{ffm}	k_1	k_2
y						
7–9	1.079	5.451	5.052	1.081	5.400	4.996
9–11	1.082	5.376	4.968	1.084	5.327	4.914
11–13	1.086	5.279	4.861	1.087	5.255	4.835
13–15	1.092	5.141	4.708	1.094	5.098	4.660
15–17	1.094	5.098	4.660	1.096	5.055	4.612
17–20	1.095	5.076	4.636	1.0985	5.002	4.554
20–25	1.096	5.055	4.612	1.100	4.971	4.519

* From reference 5. D_b, body density; D_{ffm}, density of the FFM.

APPENDIX B

Published equations that were cross-validated using our Guatemalan data

IL-AZ equation (ref 7)
SUM = triceps skinfold thickness (mm) + subscapular skinfold thickness (mm)
Females (n = 136)
SUM < 35 mm Percent fat = 1.33 × (SUM) − 0.013 × $(SUM)^2$ − 2.5; RMSE = 3.9%
SUM > 35 mm Percent fat = 0.546 × (SUM) + 9.7; RMSE = NA
Males (n = 174)
SUM < 35 mm Percent fat = 1.21 × (SUM) − 0.008 × $(SUM)^2$ − maturation-specific intercept; RMSE = 3.6%
SUM > 35 mm Percent fat = 0.783 × (SUM) + 1.6; RMSE = NA
FFM = 1 − (percent fat/100) × body weight

Fels equation (ref 8)
Females (n = 110)
FFM = 4.3383 + (0.6819 × body weight) − [0.1846 × (lateral calf skinfold thickness)] − [0.2436 × (triceps skinfold thickness)] − [0.2018 × (subscap skinfold thickness)] + [0.1822 × (ht^2/R)]; RMSE = 2.23 kg
(lateral calf skinfold thickness = medial calf skinfold thickness − 1.69)
Males (n = 140)
FFM = −2.9316 + (0.6462 × weight) − [0.1159 × (lateral calf skinfold thickness)] − [0.3753 × (midaxillary skinfold thickness)] + [0.4754 × (arm-muscle circumference)] + [0.1563 × (ht^2/R)]; RMSE = 2.31 kg
(lateral calf skinfold thickness = medial calf skinfold thickness − 1.05)

CZ-SL equation (ref 10)
Females
9–12 y: Body density = 1.088 − [0.014 × log(triceps skinfold thickness)] − [0.0360 × log(subscapular skinfold thickness)] n = 56; RMSE = 0.0118 g/mL
13–16 y: Body density = 1.114 − [0.031 × log(triceps skinfold thickness)] − [0.041 × log(subscapular skinfold thickness)] n = 62; RMSE = 0.0098 g/mL
Males
9–12 y: Body density = 1.108 − [0.027 × log(triceps)] − [0.0388 × log(subscapular skinfold thickness)] n = 66; RMSE = 0.0100 g/mL
13–16 y: Body density = 1.130 − [0.055 × log(triceps skinfold thickness)] − [0.026 × log(subscapular skinfold thickness)] n = 57; RMSE = 0.0080 g/mL
Body density is converted to percent fat by using the nomogram in reference 10 based on the equation in reference 11:
Percent fat = (4.201/body density) − 3.813
Females and males
17+ y: Percent fat determined from nomogram by using triceps and subscapular skinfold thickness (ref 30); RMSE = NA
FFM = 1 − (percent fat/100) × body weight