Prediction of body fat in 12-y-old African American and white children: evaluation of methods[1–3]

George A Bray, James P DeLany, Julia Volaufova, David W Harsha, and Catherine Champagne

ABSTRACT

Background: The prevalence of obesity is increasing in children. Validation of methods of predicting fatness in African American and white children could help to identify children at high risk.

Objective: We assessed published methods for determining body fat in 12-y-old male and female white and African American schoolchildren.

Design: The body fat of 114 children was measured with the use of dual-energy X-ray absorptiometry, underwater weighing (densitometry), measurement of skinfold thicknesses, isotope dilution ($H_2{}^{18}O$), and bioelectrical impedance analysis. Formulas derived from these data and from published reports were compared by using the Bland-Altman approach.

Results: Calculation of percentage of body fat by using an equation predicting body fat in kg and dividing by the current weight was the criterion method against which the other methods were compared. Four-compartment models had the smallest variability across the range of body fat, and 2 of these models differed from the criterion method by 1–2%. Six methods (the Pennington 4-compartment model, the Wells et al 4-compartment model, the isotope dilution model, dual-energy X-ray absorptiometry, the Pennington skinfold thickness model, and the Pennington density model) provided specificity >90%, an estimate of body fat that was within the 95% CI of the criterion method, and a difference from the criterion method that was <±2%. Bioelectrical impedance analysis was the least acceptable method.

Conclusions: A 4-compartment model in which body fat in kg is divided by current body weight and multiplied by 100 provides the best estimate of percentage of body fat. The isotope dilution and body density models provide estimates within 2% of the estimate provided by the 4-compartment model. Other models do less well. *Am J Clin Nutr* 2002;76:980–90.

KEY WORDS Dual-energy X-ray absorptiometry, bioelectrical impedance analysis, skinfold thickness, densitometry, isotope dilution, 4-compartment models, body fat, children, whites, African Americans

INTRODUCTION

The preadolescent and adolescent years are a period of rapid growth in both the fat and nonfat compartments of the body. With adolescence, gonadal hormones modify the rapidity of growth and the pattern of fat deposition. Childhood is also a time of increasing risk of developing obesity, and the prevalence of obesity in children is increasing (1, 2). Several factors, including increased food intake, reduced levels of physical activity in childhood, and a pattern of food intake in which high–energy density fast foods play an important role, are suspected in this trend (3).

Because not all children are at risk of developing obesity, methods that provide reliable estimates of body fat and obesity from childhood to adulthood are important (2). Methods for measuring body fat were evaluated in several studies (4–12). The different methods can be compared by using 1 of 3 approaches. The first approach involves comparison with the "reference" child, a technique used by Haschke et al (13) and Fomon et al (14). The second approach involves cross-validation of methods between different populations (15, 16). The third approach involves comparing the closeness of 2 different methods for estimating a variable in the same population by using the Altman and Bland approach (17). With this approach, for example, the difference between 2 methods of measuring the percentage of body fat can be evaluated by plotting the difference against the average value for the 2 methods.

In the present study, we used a cohort-validation method in a sample of children who were initially studied at the average age of 10.7 y and were then measured again 2 y later with the same methods. We also compared the results from these children with estimates of fatness from published reports by using the Altman and Bland approach (17).

SUBJECTS AND METHODS

Subjects

Children from the Baton Rouge, LA, public school system participated in this study with the approval of the Superintendent of Schools, the East Baton Rouge School Board, the LSU Institutional Review Board, and the principals of the schools involved.

[1] From the Pennington Biomedical Research Center, Baton Rouge, LA.

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[3] Address reprint requests to GA Bray, Pennington Biomedical Research Center, 6400 Perkins Road, Baton Rouge, LA 70808. E-mail: brayga@pbrc.edu.

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A total of 114 children from the initial group of 131 participated in the follow-up study. There were 30 white boys, 25 white girls, 31 African American boys, and 28 African American girls. Both the children and their parents (or parent) signed a consent form that had been approved by the LSU Institutional Review Board and that described the procedures to be used. Forty-five children were at Tanner stage 1–2.5, and the others ($n = 68$) were at Tanner stages 3–5. The African American girls were significantly more mature than were the other 3 groups ($P < 0.002$).

Procedures for measuring body composition

The methods used in this study were the same as those previously published for this group of children (18).

Anthropometry

While the children wore hospital gowns, their body weight was measured to ± 0.1 kg with an electronic scale (Detecto, Webb City, MO) that was calibrated quarterly and checked each day with a standard 25-kg weight. Height was measured to ± 0.5 cm with a wall-mounted stadiometer (Holtain, Crymych, Dyfed, United Kingdom), and body mass index (BMI) was calculated as weight/height^2 (in kg/m^2). The skinfold thickness of the triceps, biceps, subscapular area, suprailiac area, midthigh, and lateral midcalf was measured in duplicate to the nearest 1 mm with a Lange Caliper (Cambridge Scientific Instruments, Cambridge, MA). If the measurements differed by > 2 mm, a third measurement was taken and the 3 values were averaged. Sites on the right side of the body were used as described in the atlas of Lohman et al (19).

Underwater weighing

The underwater weight of the subjects was measured while they wore bathing suits and sat in a submerged chair that rested on 4 force cubes; this method was similar to that of Akers and Buskirk (20), except that a permanent tank was used in our method. Residual lung volume was determined with the use of a helium dilution technique (Sensormedics PFT, Fullerton, CA) while the subjects were submerged.

Isotope (^{18}O) dilution

Total body water was determined with $H_2{}^{18}O$ dilution, with a dose of 0.3 g $H_2{}^{18}O$/kg total body weight given to measure the turnover of body water. The ^{18}O isotope abundances were measured on a Finnigan MAT 252 gas-inlet isotope ratio mass spectrometer (Bremen, Germany) with a carbon dioxide–water equilibration device (21). Salivary enrichment was measured by comparing a baseline sample with the average of the samples collected 2 and 3 h after the dose.

Bioelectrical impedance analysis

Whole-body resistance was measured with the use of a Xitron variable frequency impedance machine (Xitron, San Diego). For the wrist, one electrode was placed to bisect the ulnar head, and the other electrode was placed just behind the middle finger. One of the ankle electrodes was placed to bisect the medial malleolus, and the other electrode was placed just behind the middle toe. The CV for body fat determined by bioelectrical impedance analysis (BIA) was 4.2%.

Dual-energy X-ray absorptiometry

Whole-body scans were performed with the Hologic QDR 2000 (Waltham, MA) in the fan beam mode. The scans were analyzed by using Hologic enhanced WHOLE BODY version 5.64 software. Body fat determined by dual-energy X-ray absorptiometry (DXA) was expressed as a percentage of total weight and as the weight of fat in kg.

Multicompartment models

Three multicompartment models are described in this study. In the first model, the percentage of body fat at 12.7 y of age is calculated by using the formula for the percentage of body fat derived from the same children at 10.7 y of age (18).

$$\%BF = [-0.423 + 1.353/\text{density} - 0.829(\text{TBW}/\text{body wt}) - 4.63(\text{BMC}/\text{body wt})]100 \qquad (1)$$

where %BF is percentage of body fat, TBW is total body water, and BMC is bone mineral content in kg. In the second model, body fat in kg is calculated by using variables fitted to these children at 10.7 y of age by reanalyzing the previous data set (18).

$$\text{BF (kg)} = -2.396 + 0.937(\text{body wt}/\text{density}) - 0.764(\text{TBW}) - 4.508(\text{BMC}) \qquad (2)$$

In the third model, the percentage of body fat at 12.7 y of age is calculated by dividing the body fat in kg derived from Equation *2* by the current body weight in kg and multiplying the result by 100.

$$\text{Calculated }\%BF = (\text{BF from Equation } 2/\text{body wt}) \times 100 \qquad (3)$$

In making comparisons with other models, we use the percentage of body fat calculated from Equation *3*.

Predictive formulas evaluated in this study

The published formulas for calculating percentage of body fat that were evaluated in this study are listed in **Table 1**.

Data analysis

The Altman and Bland approach (17) was used to compare several of the published methods listed in Table 1 against the criterion method of determining percentage of body fat that was derived from the 4-compartment model expressed in Equation *3*, which was developed from the children in the present study at 10.7 y of age. In all prediction equations, measurements made at 12.7 y of age were used. A total of 16 methods were evaluated. In each case the difference between the test method and the criterion method is expressed as a percentage of body fat. This difference was plotted against and analyzed with respect to the average body fat by using simple linear regression. The hypothesis that the slope was equal to 0 was tested in each case. This is equivalent to testing whether the 2 methods have the same error variance. The prediction interval for the difference was presented in addition to the regression line for each method. All data were analyzed with SAS version 8.1 (SAS Institute Inc, Cary, NC).

RESULTS

Description of the study population

The body-composition characteristics of the study population by sex and race are shown in **Table 2**. There were nearly equal numbers of children in each of the 4 subgroups;

TABLE 1
Formulas evaluated in the present study[1]

Method or author	Formula
BMI	Wt/Ht^2
DXA	%BF: measured
Siri (5)	%BF = (4.95/D − 4.50) × 100
Slaughter et al (7)	Males: %BF = 0.735(Tri + Calf) + 1.0
	Females: %BF = 0.610(Tri + Calf) + 5.1
Bray et al (18)	4-compartment model (optimal for %BF)
	%BF = [−0.423 + 1.353/D − 0.829(TBW/Wt) − 4.63(BMC/Wt)] × 100
	4-compartment model (optimal for kg fat)
	%BF = [−2.396 + 0.937(Wt/D) − 0.764(TBW) − 4.508(BMC)]/Wt × 100
Bray et al (18)	Isotope dilution model
	%BF = {1 − TBW/[0.76(Wt)]} × 100
Bray et al (18)	Optimal skinfold-thickness model
	%BF = 7.26 + 0.76(Bi) + 0.36(Calf) + 0.24(Thigh)
Bray et al (18)	Density model
	%BF = (−4.02 + 4.46/D) × 100
Bray et al (18)	Bioelectrical impedance analysis model
	%BF = {1 − [0.4(Ht^2/R) + 0.148(Wt) + 3.32]/[0.76(Wt)]} ×100
Deurenberg et al (22)	%BF = {Wt − 0.448(Ht^2/R) + 0.221(Wt) + 0.128(Ht) − 14.7]}Wt × 100
Ellis (23, 24)	White females: %BF = {0.642(Wt) − 0.126(Ht) − 0.606 [Age (y)] + 8.98}/Wt × 100
	African American females: %BF = {0.653(Wt) − 0.163(Ht) − 0.298[Age (y)] + 10.7}/Wt × 100
	White males: %BF = {0.534(Wt) − 1.59[Age (y)] + 3.03}/Wt × 100
	African American males: %BF = [0.594(Wt) − 0.381(Ht) + 36.0]/Wt × 100
Goran et al (25)	%BF = [0.15(Sub) + 0.36(Wt) +0.12(Tri) − 0.2(Ht^2/R) − 2.3]/Wt × 100
Schaefer et al (26)	%BF = {Wt − 0.15 + 0.65(Ht^2/R) + 0.68[Age (y)]}/Wt × 100
Suprasongsin et al (27)	%BF = [Wt − 0.524(Ht^2/R) + 0.415(Wt) − 0.32]/Wt × 100
Friedl et al (28)	4-compartment model
	%BF = [2.559/D − 0.734(TBW/Wt) + 0.942(BMC/Wt) − 1.841] × 100
Wells et al (29)	3-compartment model
	%BF = [2.22(Wt/D) − 0.764(TBW) − 1.465(Wt)]/Wt × 100
	4-compartment model
	%BF = [2.747(Wt/D) − 0.71(TBW) + 1.86(BMC) − 2.05(Wt)]/Wt × 100
Heymsfield et al (8)	4-compartment model
	%BF = (2.748/dpf − 2.051){Wt − [0.99371(TBW) + 1.279(BMC)]}/Wt × 100
	dpf = {Wt − [0.99371(TBW) +1.279(BMC)]}/{Wt/D − [TBW + 0.418(BMC)]}

[1] Wt, weight in kg; Ht, height in m; DXA, dual-energy X-ray absorptiometry; %BF, percentage of body fat; D, density; Tri, triceps skinfold thickness in mm; Calf, calf skinfold thickness in mm; TBW, total body water; BMC, bone mineral content in kg; Bi, biceps skinfold thickness in mm; Thigh, thigh skinfold thickness in mm; R, resistance at 50 Hz; Sub, subscapular skinfold thickness in mm; dpf, density of protein plus fat.

the study population was 51.8% African American and 48.2% white. The age range of the children was very narrow because almost all of the children had been recruited 2 y earlier from a single grade in school. Heights were more variable and body weight even more so. The boys tended to be slightly, but not significantly, taller (P = 0.156) and heavier (P = 0.058) than were the girls and tended to have slightly, but not significantly, more bone mineral content (P = 0.165) than did the girls. Body fat (kg) was not significantly different between the boys and the girls, but the boys had significantly more lean body mass (P = 0.0002). There were no significant differences between the races in body composition, except in bone mineral density, bone mineral content, and lean body mass, which were significantly higher in the African American children (P = 0.002).

Bland-Altman analysis

In the Altman and Bland approach (17), the difference between 2 independent methods for measuring a characteristic, such as percentage of body fat, is compared with the average value of these 2 measurements. To select the criterion method for this study, we compared the percentage of body fat determined from Equation *1* with that determined from Equation *3*. The mean percentages of body fat determined from Equations *1* and *3* were 26.3% (95% CI: 24.4%, 28.2%) and 27.8% (95% CI: 26.0%, 29.7%), respectively. Because of its smaller CI, Equation *3* was selected as the criterion method for comparison with other methods. The mean difference and 95% CI in percentage of body fat between the various methods of determining percentage of body fat and the criterion method are shown in **Table 3**.

The Altman and Bland approach (17) for evaluating the difference between each of four 4-compartment models for determining percentage of body fat and the criterion method is shown in **Figure 1**. The mean difference between the percentage of body fat calculated at 12.7 y of age in the Pennington data set with Equation *1* and the percentage of body fat calculated with Equation *3* was −1.52% (95% CI: −1.70%, −1.33%), which was significantly different from zero (P < 0.0001; Figure 1A). There was a small, but significant, positive slope, indicating a small systematic underestimation of body fat by Equation *1* as average body fat increased. The mean difference in percentage of body fat between the 4-compartment model of Wells et al (29) and the

TABLE 2
Body composition characteristics of the study population[1]

	African Americans		Whites	
	Girls (n = 28)	Boys (n = 31)	Girls (n = 25)	Boys (n = 30)
Age (y)	12.72 ± 0.13	12.86 ± 0.14	12.55 ± 0.08	12.82 ± 0.09
Weight (kg)[2]	48.55 ± 1.77	57.76 ± 2.84	50.18 ± 2.79	52.26 ± 2.65
Height (cm)	157.68 ± 1.22	158.55 ± 1.51	155.83 ± 1.43	159.16 ± 1.44
BMI (kg/m^2)[3]	23.24 ± 0.78	27.10 ± 1.09	24.15 ± 1.09	23.90 ± 0.96
%BF$_{DXA}$	24.69 ± 1.60	26.06 ± 2.28	29.64 ± 2.06	25.70 ± 1.94
Lean (kg)[2,4]	33.63 ± 0.83	38.76 ± 1.36	31.82 ± 0.88	35.55 ± 1.30
Fat (kg)	12.37 ± 1.19	16.21 ± 1.94	15.85 ± 2.17	14.23 ± 1.77
BMC (kg)[4]	1.75 ± 0.05	1.90 ± 0.07	1.63 ± 0.07	1.72 ± 0.07
Resistance (Ω)[2,3]	650.42 ± 15.71 [26]	555.36 ± 12.04	635.32 ± 11.82	595.22 ± 13.65
Total body water (kg)[2]	26.52 ± 0.63 [27]	30.90 ± 1.22 [30]	25.43 ± 0.84	28.30 ± 1.11 [29]
Density (kg/L)[3]	1.05 ± 0.004 [26]	1.04 ± 0.005	1.04 ± 0.004	1.05 ± 0.004

[1] x ± SEM; n in brackets. %BF$_{DXA}$, percentage of body fat determined by dual-energy X-ray absorptiometry; BMC, bone mineral content.
[2] There was a significant difference between the sexes, $P < 0.05$.
[3] There was a significant race × sex interaction, $P < 0.05$.
[4] There was a significant difference between the races, $P < 0.05$.

criterion method was −1.76% (95% CI: −2.10%, −1.42%), which was significantly different from zero ($P < 0.0001$; Figure 1B). The slope of the difference plotted against the average percentage of body fat was not significantly different from zero. The difference in percentage of body fat determined by the 3-compartment model of Wells et al (29) (Table 3) and that calculated with Equation *3* was even greater [−3.13% (95% CI: −3.40%, −2.87%)], meaning that the Wells et al 3-compartment model was not as good at estimating percentage of body fat as either the Wells et al 4-compartment model or the Pennington 4-compartment model (Equation *1*). Panels C and D show the difference in estimation of percentage of body fat using two 4-compartment models derived from measurements of young adults by Friedl et al (28) or older adults by Heymsfield et al (8). The mean difference in percentage of body fat between the 4-compartment

TABLE 3
Difference between each of various methods of determining percentage of body fat and the 4-compartment criterion model expressed in Equation *3*[1]

Method	$\bar{x}$ Difference[2]	Slope	Intercept
Multicompartment models[3]	%BF		
Pennington 4-compartment (Equation *1*)	−1.52 (−1.70, −1.33)	0.05[4]	−2.81[4]
Wells et al 3-compartment (29)	−3.13 (−3.40, −2.87)	−0.02	−2.69[4]
Wells et al 4-compartment (29)	−1.76 (−2.10, −1.42)	−0.02	−1.13[4]
Heymsfield et al (8)	−3.08 (−3.41, −2.76)	−0.007	−2.88[4]
Friedl et al (28)	−3.35 (−3.65, −3.05)	−0.008	−3.15[4]
Isotope and DXA models[5]			
Pennington isotope dilution (18)	0.34 (−0.09, 0.76)	−0.06[4]	1.95[4]
DXA (18)	−1.73 (−2.21, −1.26)	0.11[4]	−4.79[4]
Density models[6]			
Pennington density (18)	−1.33 (−1.84, −0.82)	−0.08[4]	0.97
Siri (5)	−3.11 (−3.63, −2.59)	0.02	−3.66[4]
Anthropometric models[7]			
Pennington optimal skinfold thickness (18)	−1.35 (−2.07, −0.64)	−0.04	−0.14
Ellis (23, 24)	−7.31 (−8.66, −5.96)	−0.03	−6.58[4]
Slaughter et al (7)	−3.77 (−4.53, −3.02)	0.07	−5.53[4]
BIA models[8]			
Pennington (18)	0.03 (−0.68, 0.73)	−0.16[4]	4.45[4]
Deurenberg et al (22)	1.91 (1.18, 2.63)	−0.29[4]	10.21[4]
Goran et al (25)	−6.45 (−7.37, −5.53)	−0.56[4]	7.40[4]
Schaefer et al (26)	0.22 (−0.60, 1.05)	0.18[4]	−4.72[4]
Suprasongsin et al (27)	−12.28 (−13.17, −11.40)	−0.39[4]	−3.82[4]

[1] %BF, percentage of body fat; DXA, dual-energy X-ray absorptiometry; BIA, bioelectrical impedance analysis.
[2] 95% CI in parentheses.
[3] *See* Figure 1.
[4] Significantly different from zero, $P < 0.05$.
[5] *See* Figure 2.
[6] *See* Figure 3.
[7] *See* Figure 4.
[8] *See* Figure 5.

The American Journal of Clinical Nutrition

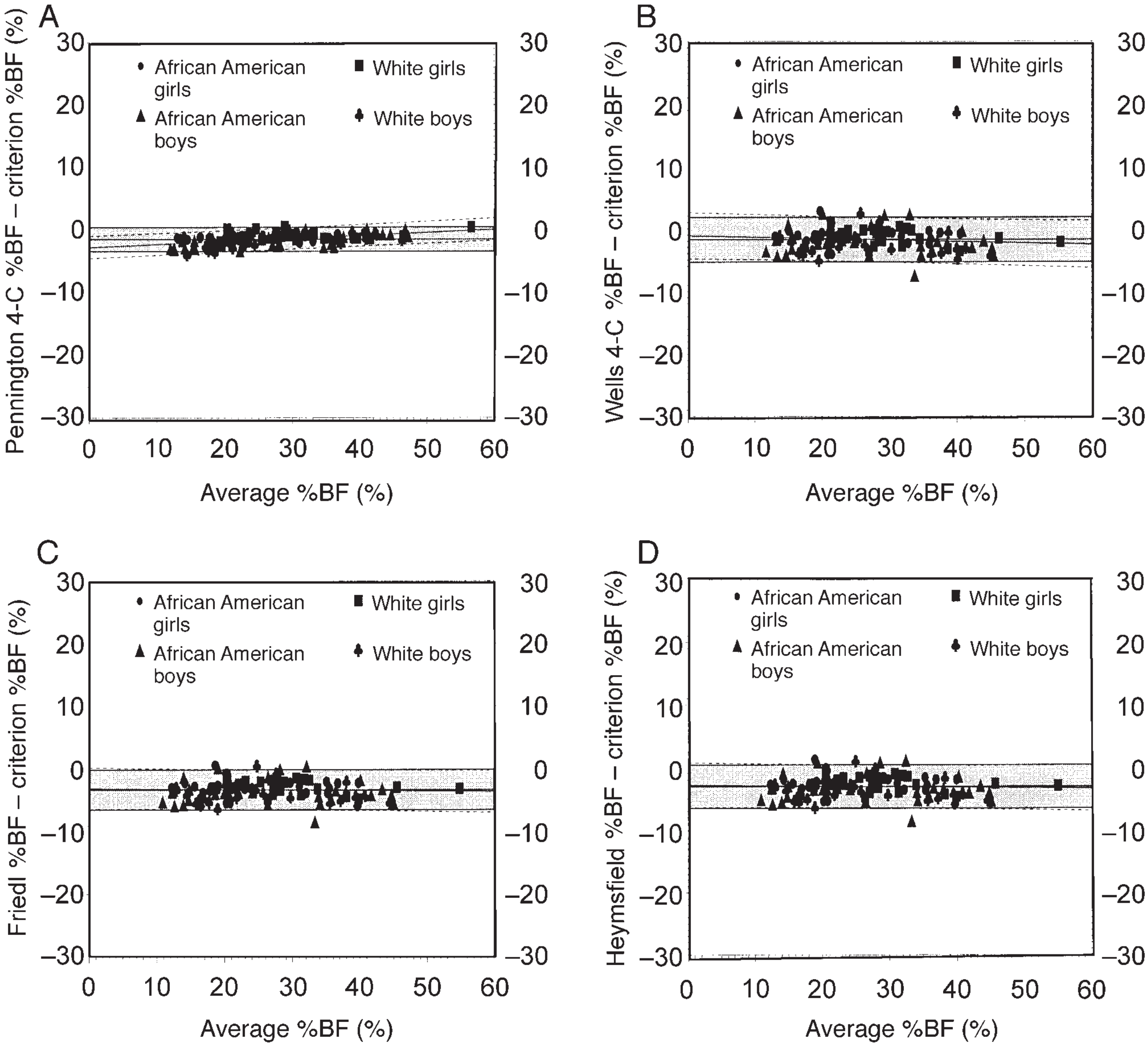

FIGURE 1. The Altman and Bland approach (17) for comparing the percentage of body fat (%BF) from each of four 4-compartment models with that from a 4-compartment criterion model derived from the study subjects. The gray area in each panel represents the mean ± 2 SDs. In each panel, the solid line is the regression line for the data and the dashed lines represent the 95% CI. The 4 test models were (A) the 4-compartment (4-C) model derived from data collected in the same children 2 y earlier, (B) the Wells et al (29) 4-compartment model in children, (C) the Friedl et al (28) 4-compartment model derived from young adults, and (D) the Heymsfield et al (8) 4-compartment model derived from older adults. In panel A, the mean difference in %BF between the methods (−1.52%) was significantly different from zero ($P < 0.0001$), and there was a small positive slope. The 2-SD range was ±2%BF. In panel B, the mean difference in %BF between the methods was −1.76%, which was significantly different from zero ($P < 0.0001$); the 2-SD range was ±3.6%BF. In panels C and D, the mean differences in %BF between the test method and the criterion method were −3.35% and −3.08%, respectively. *See* Table 3 for slopes and intercepts.

model derived from measurements of young adults made by Friedl et al (28) and our criterion method was −3.35% (95% CI: −3.65%, −3.05%) (Figure 1C). The mean difference in percentage of body fat between the 4-compartment model derived from measurements of older adults made by Heymsfield et al (8) and our criterion method was −3.08% (95% CI: −3.41%, −2.76%) (Figure 1D). Thus, neither formula was as good at estimating percentage of body fat in children as the Pennington et al (18) or Wells et al (29) formulas. The slopes for the difference between Equation *3* and the 2 adult formulas were not significantly different from zero, meaning that there was no bias in determining body fat across the range of body fat values.

The calculation of percentage of body fat by using total body water measured by isotope dilution (18) and the estimation of percentage of body fat by DXA were compared with the criterion model by using the Altman and Bland approach (17). The mean difference in percentage of body fat between the isotope dilution method and the 4-compartment criterion was 0.34% (95% CI: −0.09%, 0.76%), which was not significantly different from zero

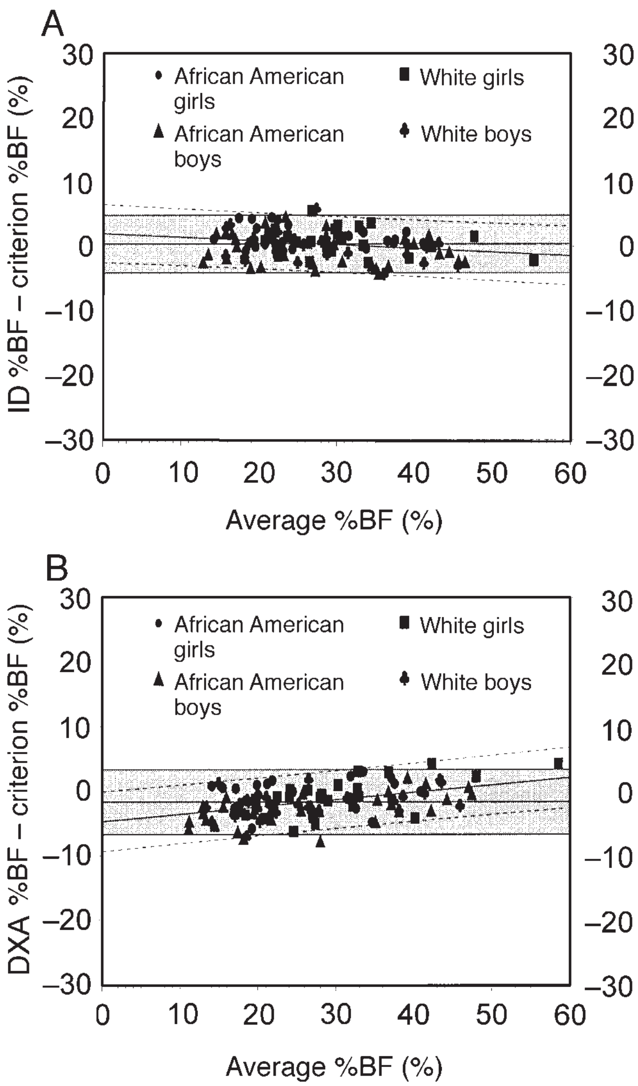

FIGURE 2. The Altman and Bland approach (17) for comparing the percentage of body fat (%BF) from (A) the isotope dilution (ID; 18) or (B) dual-energy X-ray absorptiometry (18) model with that from a 4-compartment criterion model derived from the study subjects. The gray area in each panel represents the mean ± 2 SDs. In each panel, the solid line is the regression line for the data and the dashed lines represent the 95% CI. *See* Table 3 for mean differences, 95% CIs, slopes, and intercepts.

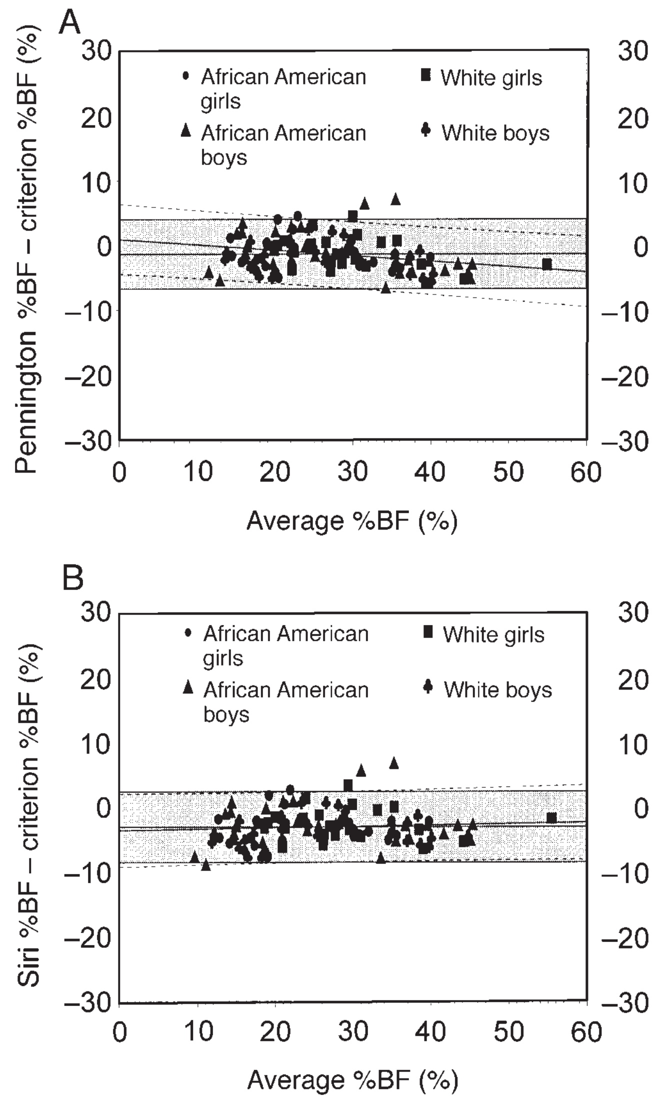

FIGURE 3. The Altman and Bland approach (17) for comparing the percentage of body fat (%BF) from (A) the Pennington density (18) or (B) Siri (5) model with that from a 4-compartment criterion model derived from the study subjects. The gray area in each panel represents the mean ± 2 SDs. In each panel, the solid line is the regression line for the data and the dashed lines represent the 95% CI. *See* Table 3 for mean differences, 95% CIs, slopes, and intercepts.

(**Figure 2**A). The small, but significant, negative slope of the difference indicates a small bias over the range of average body fat. The mean difference in percentage of body fat between the DXA method and the 4-compartment criterion model was −1.73% (95% CI: −2.21%, −1.26%) (Figure 2B), indicating that the DXA method slightly but significantly underestimated body fat. We thus conclude that isotope dilution would provide an estimate of percentage of body fat not significantly different from that of the criterion model, whereas DXA would slightly underestimate the percentage of body fat.

The relations between density models using either Equation *3* (18) or the Siri formula (3) and the 4-compartment criterion model are shown in **Figure 3**. The mean difference in percentage of body fat between the Pennington density model and the criterion model was −1.33% (95% CI: −1.84%, −0.82%). The mean difference in percentage of body fat between the Siri model and the criterion model was −3.11%, (95% CI: −3.63%, −2.59%). The slope of the difference between the Siri model and the criterion model was not significantly different from zero, but the slope of the difference between the Pennington density model and the criterion model was slightly, but significantly, negative.

The Altman and Bland approach for comparing 3 anthropometric models with the 4-compartment criterion model is shown in **Figure 4**. The Pennington optimal skinfold thickness model (18) underestimated percentage of body fat by 1.35% (95% CI: −2.07%, −0.64%) (Figure 4A). The slope of the regression line was slightly, but significantly, different from zero. The mean difference in percentage of body fat between the Slaughter et al (7) method and the criterion method was −3.77% (95% CI: −4.53%, −3.02%), or more than twice the difference between the criterion

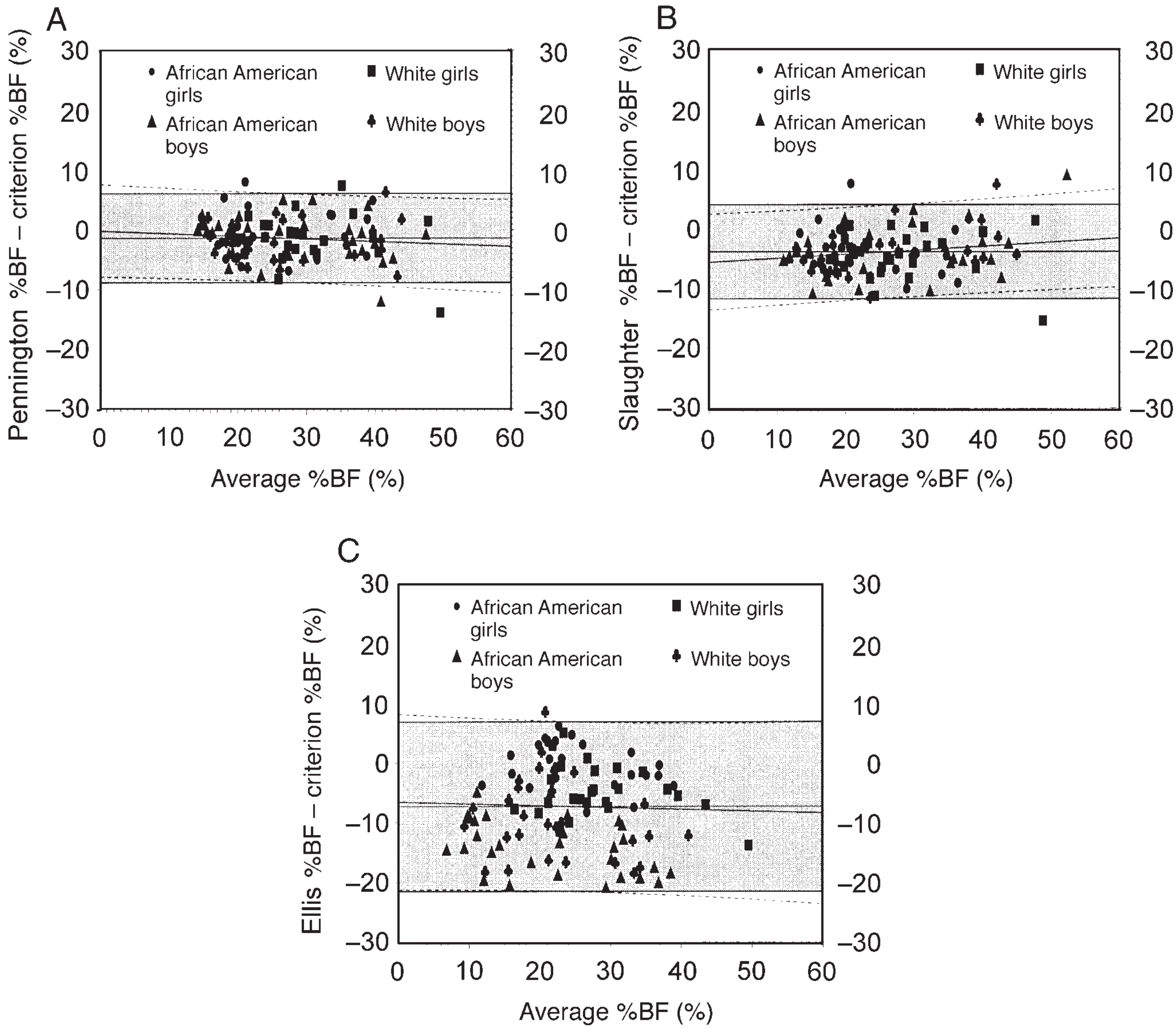

FIGURE 4. The Altman and Bland approach (17) for comparing the percentage of body fat (%BF) from each of 3 anthropometric models with that from a 4-compartment criterion model derived from the study subjects. The gray area in each panel represents the mean ± 2 SDs. In each panel, the solid line is the regression line for the data and the dashed lines represent the 95% CI. The 3 test models were (A) the Pennington optimal skinfold thickness (18) model, (B) the Slaughter et al (7) model, and (C) the Ellis et al (23, 24) model for African American and white boys and girls. *See* Table 3 for mean differences, 95% CIs, slopes, and intercepts.

method and the Pennington optimal skinfold thickness method (Figure 4B). The anthropometric formulas of Ellis et al (23, 24) underestimated percentage of body fat by 7.31% (95% CI: −8.66%, −5.96%).

The BIA models provide less satisfactory assessments of body fat compared with the 4-compartment criterion model than do the other models. The mean percentage of body fat obtained by the criterion model did not differ significantly from that obtained by either the Pennington BIA model [difference: 0.03% (95% CI: –0.68%, 0.73%)] or the Schaefer et al (26) model [difference: 0.22% (95% CI: –0.60%, 1.05%)] but did differ significantly from that obtained by each of the other 3 BIA models (22, 25, 27). All of the lines relating the difference in percentage of body fat to the average body fat in **Figure 5** had slopes that were significantly negative ($P < 0.0001$), except for the line for the model of Schaefer et al. Although the mean difference in percentage of body fat between the 4-compartment criterion model and the Pennington BIA model was close to zero (0.03%), the slope of the regression (−0.16) was significantly different from zero, and the line had an intercept at 4.45% body fat (Figure 5A). The formula from Goran et al (25) (Figure 5C) and the formula from Suprasongsin et al (27) (Figure 5E) significantly underestimated percentage of body fat over much of the range of fatness. The slopes of the difference in percentage of body fat between the criterion method and each of these 2 methods (ie, −0.56 and −0.40, respectively) were significantly different from zero, as were their intercepts. Thus, the more average the percentage of body fat a person has, the greater is the error in estimating it by BIA.

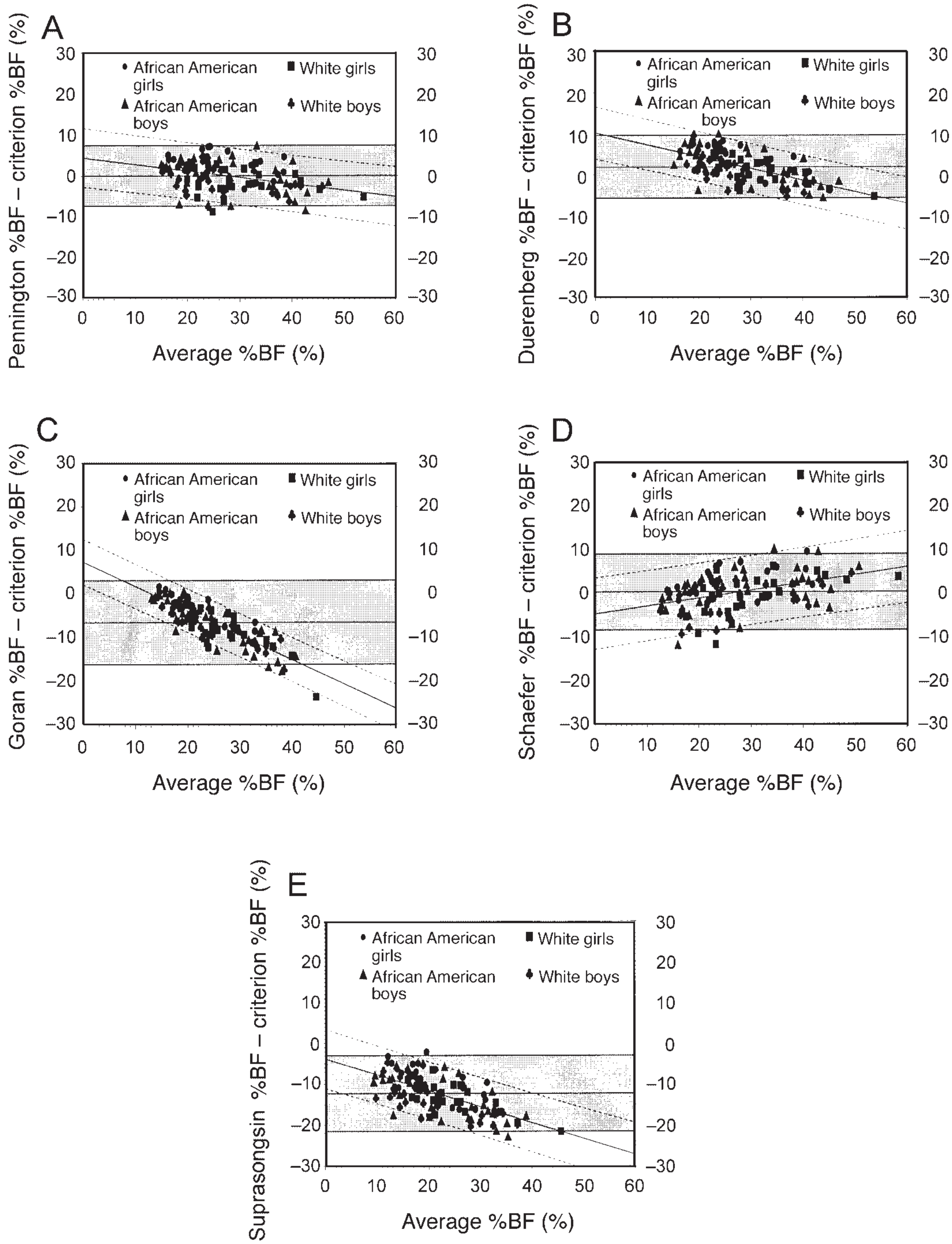

FIGURE 5. The Altman and Bland approach (17) for comparing the percentage of body fat (%BF) from each of 5 bioelectrical impedance analysis (BIA) models with that from a 4-compartment criterion model derived from the study subjects. The gray area in each panel represents the mean ± 2 SDs. In each panel, the solid line is the regression line for the data and the dashed lines represent the 95% CI. The 5 test models were (A) the Pennington BIA (18) model, (B) the Deurenberg et al (22) model; (C) the Goran et al (25) model, (D) the Schaefer et al (26) model, and (E) the Suprasongsin et al (27) model (E). *See* Table 3 for mean differences, 95% CIs, slopes, and intercepts.

Specificity and sensitivity

The specificity and sensitivity of the various methods described in Table 1 are shown in **Table 4**. To make these calculations, values for percentage of body fat calculated with Equation *3* were used to divide the subjects at the median of fatness into a group that was fatter and a group that was less fat. Specificity was defined as the ability of a method to correctly assign a fat person to the fat group, and sensitivity was defined as the ability of the method to correctly assign a person to the less-fat group if that is where the person belonged. Specificity was >90% for all of the methods except 3 of the BIA methods (18, 22, 26). Thus, if a person were fat, the likelihood of that person being classified as fat was >90% for almost all of the methods. Sensitivity was >90% for the 4-compartment models for children (18, 29) and for the isotope dilution method (18). The method of Deurenberg et al (22) also had a high sensitivity but

TABLE 4
Specificity and sensitivity of methods of measuring percentage of body fat relative to 4-compartment criterion model[1]

Method	Specificity	Sensitivity
Multicompartment models		
Pennington 4-compartment (Equation *1*)	1.00	0.93
Wells et al 3-compartment (29)	1.00	0.84
Wells et al 4-compartment (29)	0.98	0.91
Friedl et al (28)	1.00	0.82
Heymsfield et al (8)	1.00	0.87
Isotope and DXA models		
DXA (18)	0.98	0.82
Pennington isotope dilution (18)	0.94	0.93
Density models		
Pennington density (18)	0.98	0.91
Siri (5)	1.00	0.85
Anthropometric models		
Pennington optimal skinfold thickness	0.94	0.82
Ellis (23, 24)	0.96	0.47
Slaughter et al (7)	0.98	0.71
BIA models		
Pennington (18)	0.87	0.84
Deurenberg et al (22)	0.65	0.93
Goran et al (25)	1.00	0.45
Schaefer et al (26)	0.89	0.84
Suprasongsin et al (27)	1.00	0.11

[1] DXA, dual-energy X-ray absorptiometry; BIA, bioelectrical impedance analysis.

TABLE 5
Comparison between methods of estimating percentage of body fat and the 4-compartment criterion model[1]

Method	R^2	$\bar{x}$[2]
		%BF
Multicompartment models		
Pennington 4-compartment (Equation *1*)	0.99	26.3 (24.4, 28.2)
Wells et al 3-compartment (29)	0.98	24.7 (22.9, 26.5)
Wells et al 4-compartment (29)	0.96	26.1 (24.3, 27.9)
Heymsfield et al (8)	0.97	24.8 (23.0, 26.6)
Friedl et al (28)	0.97	24.5 (22.7, 26.3)
Isotope and DXA models		
Pennington isotope dilution (18)	0.95	28.2 (26.5, 29.9)
DXA (18)	0.95	26.4 (24.4, 28.4)
Density models		
Pennington density (18)	0.92	26.8 (25.1, 28.4)
Siri (5)	0.92	25.0 (23.2, 26.8)
Anthropometric models		
BMI	0.67	24.7 (23.6, 25.7)
Pennington optimal skinfold thickness (18)	0.85	26.9 (25.2, 28.6)
Ellis (23, 24)	0.51	20.8 (19.1, 22.5)
Slaughter et al (7)	0.85	24.4 (22.6, 26.3)
BIA models		
Pennington (18)	0.85	28.2 (26.6, 29.7)
Deurenberg et al (22)	0.87	30.0 (28.7, 31.4)
Goran et al (25)	0.88	21.7 (20.6, 22.7)
Schaefer et al (26)	0.86	28.4 (26.3, 30.6)
Suprasongsin et al (27)	0.80	15.8 (14.6, 17.0)

[1] The mean percentage of body fat from the 4-compartment criterion model was 27.8% (95% CI: 26.1%, 29.7%). R^2 was obtained from regression on the 4-compartment criterion model that was optimal for kilograms. DXA, dual-energy X-ray absorptiometry; BIA, bioelectrcal impedance analysis.
[2] 95% CI in parentheses.

had the lowest specificity. DXA, the Pennington optimal skinfold thickness model, the Pennington BIA model, the Friedl et al (28) 4-compartment model, the Wells et al (22) 3-compartment model, and the Schaefer et al (26) BIA model each had sensitivity between 80% and 89%. Three models (23–25, 27) (with 6 formulas) had low sensitivity (< 50%).

Estimating percentage of body fat

Finally, a comparison between each of the 17 models for estimating percentage of body fat and the 4-compartment criterion model is shown in **Table 5**. The percentage of body fat obtained from the criterion model was compared with that obtained from each of the other models. The other multicompartment models provided good estimates, as did the isotope dilution model. The errors in using measurement of skinfold thicknesses or BIA were larger than for the multicompartment and isotope dilution models.

DISCUSSION

Several methods of measuring percentage of body fat in children were compared with a 4-compartment criterion method by using the Altman and Bland approach (17). In the article in which this approach was proposed, Altman and Bland worked from the assumption that, a priori, there was no basis for selecting between methods. They then proposed plotting the difference between 2 methods obtained in a group of subjects against the average of these 2 methods. The methods that most closely estimated the real value would be likely to have a difference that was close to or equal to zero and to have a small variation. In the present study we used a 4-compartment model for estimating percentage of body fat as the criterion model (Equation *3*).

Compared with the criterion model, 3 models had a difference in percentage of body fat of < 1%. These included the Pennington isotope dilution model (18), the Pennington BIA model (18), and the Schaefer et al (26) BIA model. However, compared with the criterion model, the 2 BIA models significantly underestimated (Pennington model) or overestimated (Schaefer model) percentage of body fat as average body fat increased. On the other hand, the isotope dilution model appears to provide good estimates across the entire range of body fat values.

Several other models differed from the criterion model in percentage of body fat by 1–2% (Table 2). Of these, the Pennington (18) and Wells et al (29) 4-compartment models developed in children appear to be good models. The two 4-compartment models developed in adults (8, 28) provided similar estimates of fat in children but differed from the criterion model in percentage of body fat by > 3%. One explanation for the lower average value of percentage of body fat obtained with these 2 methods may be the difference in hydration between children (75%; 18, 30, 31) and adults (8).

Among the methods evaluated, several methods differed from the criterion method in percentage of body fat by 3–4%. In addition to the 2 adult 4-compartment models mentioned above, these methods include the Wells et al (29) 3-compartment model, the Siri (5) density model, and the Slaughter et al (7) skinfold model. The remaining methods (23–25, 27), including 2 methods based on the use of BIA, were less satisfactory.

Because all of the measurements needed to calculate percentage of body fat with a 4-compartment model may not be available, we asked which of the single methods provided the best choice. After using the Altman and Bland approach to evaluate this question, we conclude that several methods, including DXA, density, total body water, and skinfold thickness methods, may be appropriate. To focus the choice more sharply, the mean values of percentage of body fat for these methods are shown in Table 5. The mean percentage of body fat from the 4-compartment criterion model was 27.8%. Those methods that include this mean within their 95% CI are worth considering. These include the isotope dilution model, the DXA model, the Pennington density model, the Pennington optimal skinfold thickness model, the Pennington BIA model, and the Schaefer et al BIA model. The rest of the models failed to include 27.8% in their 95% CI and would therefore be less satisfactory.

As a technique to measure water and thus calculate fat, BIA appears to provide a biased underestimate of body fat that in 3 methods worsened significantly as body fat increased. Of the 5 BIA methods that we evaluated, 2 of them severely underestimated body fat at moderate and high values of body fat, and 2 others moderately underestimated body fat. Even the Pennington formula that was developed with these children 2 y earlier had this bias. One explanation for this problem lies in the nature of the method. BIA is designed to measure body water by the resistance to an alternating current. Compared with data from the 4-compartment criterion model, the BIA data suggest that as the amount of body fat increases, the resistance in the BIA measurement is systematically biased, possibly from the increase in fat mass, which has a lower hydration than that of lean tissues and thus alters the electrical conductivity of the alternating current. The data of Hewitt et al (30) are consistent with this idea. They showed a significant negative relation between the difference in percentage of body fat calculated from density alone and that calculated from density, water, and bone and the water content of fat free mass (30). Thus, as the percentage of water in the fat-free mass increased, the underestimation of fat by these 2 approaches increased, which is what our data show as well. These observations make it difficult to interpret data from studies that use BIA to determine body fat.

BMI is widely used as an index of obesity. In a previous article (18), we noted that there was no relation between percentage of body fat and BMI in leaner children but that there was a significant positive correlation in fatter children. We reevaluated the relation between BMI and body fat in the present study. BMI, like most of the other methods, underestimated percentage of body fat. As in the previous analysis, BMI was almost useless as an estimator of percentage of body fat in normal-weight children, but it had a significant positive correlation with percentage of body fat in the fatter children.

We evaluated the specificity and sensitivity of the 17 formulas presented in Table 1. The specificity tells you the likelihood of classifying someone appropriately, and the sensitivity tells you the likelihood of misclassifying someone. As shown in Table 4, most of the methods provide a specificity of $>90\%$ and a sensitivity of $>80\%$. The exceptions to this are the BIA formulas of Deurenberg et al (22), Goran et al (25), and Suprasongsin et al (8) and the anthropometric formulas of Ellis (23, 24) and Slaughter et al (7). The multicompartment models provide the highest specificity and sensitivity. Of the single instrument methods, however, the DXA, isotope dilution, and density models provide high specificity and sensitivity.

This analysis of methods of determining body composition in children clearly shows that some methods are better than others. The 4-compartment models developed in children are among the most reliable. Of the single methods, the isotope dilution, DXA, Pennington optimal skinfold thickness, and Pennington density methods are only a little less reliable than are the multicompartment models. The BIA models and the anthropometric models are clearly less accurate.

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