Development of bioelectrical impedance analysis prediction equations for body composition with the use of a multicomponent model for use in epidemiologic surveys[1–4]

Shumei S Sun, W Cameron Chumlea, Steven B Heymsfield, Henry C Lukaski, Dale Schoeller, Karl Friedl, Robert J Kuczmarski, Katherine M Flegal, Clifford L Johnson, and Van S Hubbard

ABSTRACT

Background: Previous studies to develop and validate bioelectrical impedance analysis (BIA) equations to predict body composition were limited by small sample sizes, sex specificity, and reliance on reference methods that use a 2-component model.

Objective: This study was designed to develop sex-specific BIA equations to predict total body water (TBW) and fat-free mass (FFM) with the use of a multicomponent model for children and adults.

Design: Data from 5 centers were pooled to create a sample of 1474 whites and 355 blacks aged 12–94 y. TBW was measured by dilution, and FFM was estimated with a multicomponent model based on densitometry, isotope dilution, and dual-energy X-ray absorptiometry.

Results: The final race-combined TBW prediction equations included stature^2/resistance and body weight (R^2 = 0.84 and 0.79 and root mean square errors of 3.8 and 2.6 L for males and females, respectively; CV: 8%) and tended to underpredict TBW in black males (2.0 L) and females (1.4 L) and to overpredict TBW in white males (0.5 L) and females (0.3 L). The race-combined FFM prediction equations contained the same independent variables (R^2 = 0.90 and 0.83 and root mean square errors of 3.9 and 2.9 kg for males and females, respectively; CV: ≈6%) and tended to underpredict FFM in black males (2.1 kg) and females (1.6 kg) and to overpredict FFM in white males (0.4 kg) and females (0.3 kg).

Conclusion: These equations have excellent precision and are recommended for use in epidemiologic studies to describe normal levels of body composition. *Am J Clin Nutr* 2003;77:331–40.

KEY WORDS Bioelectrical impedance analysis, prediction equations, total body water, fat-free mass, multicomponent model, epidemiologic surveys

INTRODUCTION

Assessment of human body composition includes the measurement of fat, fat-free mass (FFM), and total body water (TBW). FFM may be further separated into lean soft tissue, including water, and bone. Excesses or depletions of fat and FFM are associated with an increased risk of some chronic diseases. The amount of FFM is considered to be directly correlated with health and longevity (1) and is an important predictor of survival in some critical illnesses and malignancies (2). A significant component of the change in body weight with aging is attributable to an increase in body fat or a decrease in TBW secondary to a decrease in muscle or body cell mass (3–5). Overweight and obesity are associated with morbidity and mortality from cardiovascular disease (6), and their prevalence has increased at all ages in the US population (7–9). Currently, assessment and screening of overweight and obesity frequently rely on the use of anthropometry in the form of the body mass index (BMI), skinfold thicknesses, and body circumferences. One limitation of this anthropometric approach is the reduced ability to differentiate levels of fatness and leanness among individuals (10, 11).

An alternative method for body-composition assessment is bioelectrical impedance analysis (BIA). This method has practical features similar to anthropometry (eg, safety, cost-effectiveness, convenience for the patient, and ease of use), and it has been used in large-scale studies of body composition and assessment of body

[1] From the Department of Community Health, Wright State University School of Medicine, Dayton, OH (SSS and WCC); the Obesity Research Center, St Lukes–Roosevelt Hospital, Columbia University, New York (SBH); the US Department of Agriculture, Agricultural Research Service, Grand Forks Human Nutrition Research Center, Grand Forks, ND (HCL); Nutritional Sciences, University of Wisconsin, Madison (DS); the Military Operational Medicine Program, Military Medical Research and Materiel Command, Frederick, MD (KF); the National Institutes of Health, Division of Digestive Diseases and Nutrition (RJK) and the Division of Nutrition Research (VSH), National Institute of Diabetes and Digestive and Kidney Diseases, Bethesda, MD; and the Centers for Disease Control and Prevention, National Center for Health Statistics, Division of Health Examination Statistics, Hyattsville, MD (KMF and CLJ).

[2] Mention of a trademark or proprietary product does not constitute a guarantee of warranty of the product by the US Department of Agriculture and does not imply its approval to the exclusion of other products that may also be suitable. US Department of Agriculture, Agricultural Research Service, Northern Plains Area, is an equal opportunity and affirmative action employer, and all agency services are available without discrimination.

[3] Supported by the Centers for Disease Control and Prevention, the US Army Medical Research and Materiel Command, the Nutritional Services Branch, the National Institute of Diabetes and Digestive and Kidney Diseases, and grants HD 27063, HD 12252, and HL 13404 from the National Institutes of Health.

[4] Reprints not available. Address correspondence to SS Sun, Lifespan Health Research Center, Department of Community Health, 3171 Research Boulevard, Kettering, OH 45420. E-mail: shumei.sun@wright.edu.

Received April 4, 2001.

Accepted for publication March 5, 2002.

fluid status (12). BIA measures of resistance and impedance are proportional to body water volume, if body electrolyte status is normal, and to the length of the conductor or stature (eg, stature^2/resistance). This method uses regression analysis to derive prediction models to estimate TBW and FFM (12–14).

A limitation of previous BIA prediction equations has been the use of the 2-component model (fat and fat-free) as the reference method. Methods such as hydrometry (15), hydrodensitometry (16), and whole-body counting of ^{40}K (17) assume a constant composition of the fat-free body and thus are limited in discriminating differences in body composition when factors such as physical activity, illness, and aging affect a person. However, these limitations can be overcome with a multicompartmental model of human body composition that considers interindividual differences in the chemical composition of the fat-free body (18).

This report describes the results of a multicenter study to develop and validate BIA equations to predict body composition. These broadly applicable equations for TBW and FFM are to be used to provide estimates of body composition for children and adults in the United States from the third National Health and Nutrition Examination Survey (NHANES III) (19, 20). This information will address the interests in characterizing the increasing prevalence of obesity in the United States and overcome some of the limitations of BMI and anthropometry to discriminate differences in body composition.

SUBJECTS AND METHODS

Study sample

Data from 5 independent research centers were used to develop the prediction equations. The New York data set was from the Obesity Research Center, St Lukes Hospital, New York; the North Dakota data set was from the US Department of Agriculture, Grand Forks, ND; the Fels Longitudinal Study data were from the Lifespan Health Research Center, Kettering, OH; the Chicago data set was from the University of Chicago; and the US Army data set was from the US Army Research Institute of Environmental Medicine, Natick, MA. These groups had been recruited previously as participants in body-composition studies at these institutions. At the time of this earlier testing, the participants resided near each of their respective study sites, except for the participants in the Fels Longitudinal Study, ≈25% of whom resided in the midwest, northeast, southern, and far western regions of the continental United States. All of the black subjects were from the New York, Chicago, and US Army study sites. The number of white participants was relatively large compared with the number of black participants: 116 white and 14 black children between 12 and 18 y of age.

Measured variables

Descriptions of the 5 separate studies and their body-composition and research methods were published previously (15, 16, 18, 21, 22). Stature and weight were measured at all study locations with the use of standardized techniques (23). Resistance and reactance were measured at 50 kHz with an RJL BIA instrument (model 101; RJL Systems, Inc, Detroit) at all of the study sites. The tetrapolar resistance and reactance measurements were collected in a standardized manner in each study between the right wrist and the right ankle with the participant supine. The impedance index (stature^2/resistance; in cm^2/Ω) was calculated for each person.

TBW (in L) was measured by deuterium dilution corrected for natural abundance and isotope exchange (24), except for a small number of participants at New York who were evaluated with the use of equivalent tritium dilution (25). Body density (BD; in g/cm^3) was determined by hydrostatic weighing corrected for residual volume (26). Total-body bone mineral content (BMC; in g) was measured with the use of dual-energy X-ray absorptiometry (DXA) machines with version 3.6 software (Lunar Inc, Madison, WI) at each study site, except at North Dakota, where a QDR 2000 DXA (Hologic, Inc, Bedford, MA) was used with software version 5.71. These measured values were used in the following multicomponent body-composition model (18). This model is derived by the combination of 4-compartment models for body weight and body volume that assume known and constant densities for each component (27).

$$\begin{aligned} \text{TBF} &= 2.513\ \text{BV} - 0.739\ \text{TBW} \\ &+ 0.947\ \text{BMC}/1000 - 1.79\ (\text{weight}) \end{aligned} \qquad (1)$$

where TBF is total body fat, BV is body volume (in L) calculated as body weight divided by BD from hydrostatic weighing, BMC is from DXA, and TBW is from measured TBW. The FFM of each person was calculated as weight − TBF.

Statistical methods

Descriptive statistics including means and SDs were calculated for age, stature, weight, BMI, resistance, stature^2/resistance, BD, BMC, TBW, and FFM for each sex and racial group with the use of SAS (28). Comparisons of the means among race and sex groups were made by using a two-factor general linear model (SAS PROC GLM) with class variables: sex and race for the validation sample. The interaction between sex and race was included in the GLM procedure. The GLM is equivalent to analysis of variance if the number of observations is equal among the groups. If a significant interaction between sex and race was observed, comparisons were made between sex, within race, and vice versa. Similar analyses were performed for the cross-validation sample.

The combined data in the total sample from these 5 study sites were separated into validation and cross-validation samples. These 2 subsamples were used to select the independent variables and formulate the preliminary prediction equations for TBW and FFM and to evaluate their performance. *Precision* is the ability to explain the variation of the dependent variable within the sample from which it was derived. *Accuracy* measures the performance of a prediction equation when it is applied to an independent sample. The precision and accuracy of a prediction equation are affected by the measurement errors of the independent and dependent variables, the biological relation of the dependent variable with the independent variables and the size and the nature of the sample. After the independent variables were selected and the preliminary equations formulated and cross-validated, a set of final prediction equations was refitted to data from the total sample.

Variable selection and preliminary equation development

The validation sample consisted of data from 1304 participants: 412 white males, 622 white females, 114 black males, and 156 black females aged 12–94 y from 3 of the New York, North Dakota, and Fels study centers (**Table 1**). Three participants whose ratio of TBW to weight was > 0.8 L/kg were excluded from the analysis because they were assumed to be outside of the normal

TABLE 1
Number of participants by study site, sex, and race

	Validation sample				Cross-validation sample			
	Whites		Blacks		Whites		Blacks	
Study site	Males	Females	Males	Females	Males	Females	Males	Females
New York	228	335	114	156	—	—	—	—
North Dakota	4	95	—	—	—	—	—	—
Fels	180	192	—	—	115	115	—	—
Chicago[1]	—	—	—	—	22	93	18	55
US Army	—	—	—	—	45	50	8	4
Total	412	622	114	156	182	258	26	59

[1] Fat-free mass not available.

physiologic range (3–5). The New York sample was used in the validation sample because it contained the largest number of black subjects. The Fels data contained the largest number of white subjects, and they were included in both the validation and cross-validation samples.

The cross-validation sample consisted of 525 participants: 182 white males, 258 white females, 26 black males, and 59 black females aged 12–69 y from the Chicago, US Army, and Fels study centers (Table 1). There were 188 participants in the Chicago study, but the variables necessary to calculate FFM from the multicompartment body-composition model were not available in the Chicago study. Therefore, the Chicago data were used only to develop the TBW prediction equations. In the US Army study, 6 participants had TBW-weight ratios > 0.8 L/kg and were excluded; data from the remaining 107 Army participants were analyzed. The Chicago and US Army samples were used in the cross-validation sample because they contained black subjects.

GLM was used for sex and race differences in the variables age, stature, weight, BMI, resistance, stature^2/resistance, BD, BMC, TBW, and FFM. In addition to main effects of sex and race differences, the interaction effects between sex and race were considered also. If the variables had significant interaction effects, the race- or sex-associated differences were compared, stratified by race and sex, respectively.

An all-possible-subsets regression analysis was performed separately for TBW and FFM, with the possible independent variables of age, weight, stature, BMI, stature^2/resistance, resistance, and reactance included in each analysis. This procedure develops and evaluates the preliminary equations that contain all the possible combinations of independent variables, ie, 2^p+1 equations, when there are p potential independent variables (29). The preliminary equations were selected by measures of goodness-of-fit statistics, including the R^2 values adjusted for the df, root mean square error (RMSE), and Mallows' Cp statistic (30). R^2, the coefficient of determination, is the proportion of the total variance in the dependent variable that is explained by the independent variables in an equation. The larger the R^2 value, the better the equation fits the data. In general, as the number of independent variables in an equation increases, the precision of the equation improves, but the rate of improvement in precision decelerates as the number of independent variables increases. Mallows' Cp statistic is an index of the appropriate number of independent variables in an equation. Ideally, one selects a prediction equation (from a set of possible prediction equations) with the Cp value that is close to the number of independent variables.

A variance inflation factor for each independent variable was also calculated to evaluate multicollinearity (29). In the presence of multicollinearity, prediction equations are sensitive to the addition or deletion of a variable or subject. Such equations tend to be sample specific and will not perform well when applied to independent samples. As a result, the developed equations that contained both weight and BMI were not considered further, as were those equations where the independent variables had nonsignificant regression estimates.

Cross-validation is the application of a prediction equation to a sample independent from the one used to construct the equation. Pure error is a measure of the performance of a prediction equation when applied to an independent sample (14). Pure error is calculated as the square root of the sum of squared differences between the observed and the predicted values divided by the number of subjects in the cross-validation sample. The smaller the pure error, the greater the accuracy of the equation. There is no criterion value for the pure error that indicates successful cross-validation, but the pure error should be similar to the value of the RMSE of the same equation from its validation. The selected preliminary equations were cross-validated by using the independent samples from Chicago, the US Army, and the Fels study, and the pure error was used to evaluate the cross-validation results from these independent samples.

The final equations

To derive the final race-combined equations, the independent variables determined from the preliminary equations were used in a regression analysis on the total data set from the combined 5 samples. These final race-combined equations were statistically validated by the PRESS (prediction of sum of squares) statistics for whites and blacks in the sample separately and for both races combined, ie, the total sample (29). The PRESS statistic is a measure of how well an equation performs when applied to independent samples. This cross-validation procedure is used when insufficient independent data are available (29). The PRESS statistic is obtained by *1*) fitting a regression equation with one observation excluded, *2*) obtaining the predicted value of the excluded observation, *3*) calculating the residual for that predicted value (observed − predicted), 4) repeating steps 1–3 for all observations, *5*) taking the sum of squares of all residuals, and *6*) deriving the PRESS statistic by taking the square root of the sum of squares of the residuals divided by the total number of observations. To obtain a PRESS statistic, the square root of the sum of squares of the residuals was used. Validation using the PRESS procedure is similar to applying the equation to an independent

TABLE 2
Descriptive statistics for the validation and cross-validation samples of white and black males and females

Sample and variable	White males	Black males	White females	Black females
Validation				
No. of subjects	412	114	622	156
Age (y)[1,2]	41.9 ± 20.1[3]	48.3 ± 19.3	42.4 ± 19.5	51.7 ± 18.4
Weight (kg)	75.6 ± 16.2[4,5]	79.9 ± 15.4[6]	65.4 ± 15.6[6]	73.5 ± 17.1
Stature (cm)[1,7]	174.3 ± 11.2	173.7 ± 8.6	162.9 ± 8.1	161.1 ± 8.7
BMI (kg/m^2)	24.6 ± 4.1[4]	26.4 ± 4.4[6]	24.5 ± 5.3[6]	28.1 ± 5.7
Resistance (Ω)[1,2,7]	475.9 ± 71.5	463.8 ± 66.8	571.8 ± 70.0	549.4 ± 71.8
Stature^2/resistance (cm^2/Ω)[1,7]	65.8 ± 13.2	66.9 ± 13.5	47.3 ± 7.5	48.2 ± 8.1
Fat-free mass (kg)[1,2,7]	58.8 ± 11.2	62.9 ± 11.0	43.4 ± 6.8	46.8 ± 8.1
Total body water (L)[1,2,7]	43.6 ± 9.3	47.6 ± 8.5	32.2 ± 5.4	35.6 ± 6.4
Bone density (g/cm^3)	1.048 ± 0.018[5]	1.047 ± 0.019[6]	1.026 ± 0.020[6]	1.016 ± 0.019
Bone mineral content (kg)	2.8 ± 0.6[4,5]	3.2 ± 0.6[6]	2.2 ± 0.4[6]	2.4 ± 0.4
Cross-validation				
No. of subjects	182	26	258	59
Age (y)[1,7]	30.1 ± 14.3	37.2 ± 15.2	32.2 ± 12.8	37.1 ± 10.8
Weight (kg)	75.5 ± 20.1[5]	83.9 ± 21.9	64.1 ± 17.0	80.5 ± 21.2
Stature (cm)	174.9 ± 11.2[5]	179.3 ± 9.8[6]	164.1 ± 8.1	163.4 ± 6.0
BMI (kg/m^2)	24.4 ± 5.0	25.8 ± 5.2[6]	23.6 ± 5.6[6]	30.0 ± 7.2
Resistance (Ω)	486.6 ± 74.6[5]	459.4 ± 59.4[6]	589.3 ± 73.5[6]	520.1 ± 71.2
Stature^2/resistance (cm^2/Ω)[1,2,7]	64.9 ± 13.4	71.6 ± 13.9	46.6 ± 7.8	52.4 ± 8.3
Fat-free mass (kg)[1,2,7]	58.0 ± 13.0	73.1 ± 8.6	41.6 ± 7.2	47.6 ± 5.8
Total body water (L)[1,2,7]	43.0 ± 10.0	50.4 ± 10.5	31.3 ± 5.6	36.4 ± 5.8
Bone density (g/cm^3)[1,2,7]	1.051 ± 0.02	1.066 ± 0.021	1.031 ± 0.02	1.050 ± 0.012
Bone mineral content (kg)[1,2,7]	2.9 ± 0.7	3.8 ± 0.6	2.3 ± 0.5	2.6 ± 0.4

[1] No sex and race interaction (general linear model).
[2] Significant main effect of race, $P < 0.05$ (general linear model).
[3] $\bar{x}$ ± SD.
[4] Significantly different from black males, $P < 0.05$ (stratified analysis due to the sex and race interaction effect from the general linear model).
[5] Significantly different from white females, $P < 0.05$ (stratified analysis due to the sex and race interaction effect from the general linear model).
[6] Significantly different from black females, $P < 0.05$ (stratified analysis due to the sex and race interaction effect from the general linear model).
[7] Significant main effect of sex, $P < 0.05$ (general linear model).

sample because the PRESS residual is obtained for the observations that are not included in the data when the equation is derived.

RESULTS

Descriptive statistics

In the validation sample in **Table 2**, black males and females were significantly older than whites. Black males and females were also significantly heavier ($P < 0.05$) than whites, and males were heavier than females. Males were significantly taller than females, and white females were slightly but significantly taller than black females. Blacks had significantly larger mean BMIs than did whites, and black females had larger mean BMIs than did black males. Whites had larger mean resistance values than did blacks, and females had larger mean resistance values than did males. Males had larger mean stature^2/resistance values than did females. Blacks had significantly larger mean FFM and TBW values than did whites, and males had significantly larger mean FFM and TBW values than did females. Mean BMD values were significantly larger for males than for females, and white females had larger mean BMD values than did black females. Blacks had significantly larger mean BMC values than did whites, and males had significantly larger mean BMC values than did females.

In the cross-validation sample in Table 2, blacks were again significantly ($P < 0.05$) older than whites. As in the validation sample, blacks were significantly heavier than whites, males were heavier than females, and males were significantly taller than females. Blacks females had significantly larger mean BMIs than did white females and black males. White females had significantly larger mean resistance values than did black females and white males, and black females had significantly larger mean resistance values than did black males. Blacks had significantly larger mean stature^2/resistance, FFM, TBW, BMD, and BMC values than did whites, and females had significantly larger mean values than did males.

Variable selection and preliminary equation development

Two sets of preliminary equations were developed for TBW and FFM from the validation sample for each sex. A race-combined set of preliminary equations for males and females included both whites and blacks, whereas the other set of preliminary equations was for whites only. The race-combined TBW equations were not significantly different from the corresponding white-only TBW equation when a statistical test similar to that of the F ratio was used to test for the equality of variance, ie, RMSE. There were significant differences in the parameter estimates between the female race-combined TBW preliminary equation and the TBW equation for white females only.

The race-combined preliminary FFM equations for males and females differed from the corresponding FFM preliminary equations for whites only in that age and resistance were included in the latter equations, and there was no difference in RMSE from the F test. There were again some significant differences in the

TABLE 3
R^2 and root mean square error (RMSE) values for the independent variables with total body water and fat-free mass for white and black males and females

	Total body water				Fat-free mass			
	White males		Black males		White females		Black females	
	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
Total body water								
Stature^2/resistance (cm^2/Ω)	0.79	4.3	0.80	3.8	0.73	2.8	0.75	3.2
Weight (kg)	0.68	5.3	0.66	5.0	0.53	3.7	0.69	4.0
Resistance (Ω)	0.58	6.0	0.59	5.5	0.47	4.0	0.39	5.0
Fat-free mass								
Stature^2/resistance (cm^2/Ω)	0.86	4.6	0.79	5.0	0.78	3.3	0.75	4.1
Weight (kg)	0.74	6.1	0.66	6.4	0.61	4.3	0.70	4.5
Resistance (Ω)	0.61	7.5	0.58	7.1	0.47	5.1	0.39	6.3

corresponding parameter estimates for weight for the preliminary FFM equations for females.

The race-combined TBW equations for males and females had stature^2/resistance and weight as independent variables, and the independent variables for the race-combined FFM equations for males and females were stature^2/resistance, weight, and resistance for both sexes. In both the TBW and FFM equations, stature^2/resistance as a single independent variable had the highest R^2 value of all the possible independent variables (**Table 3**). The R^2 values for stature^2/resistance with TBW ranged from 0.73 to 0.80 and from 0.75 to 0.86 with FFM for females and males, respectively. Body weight had the second highest R^2 values with TBW and FFM in both sexes, with R^2 ranging from 0.53 to 0.68 with TBW and from 0.61 to 0.74 with FFM for males and females, respectively. The R^2 for resistance, the third most important independent variable, was 0.39–0.58 with TBW and was 0.39–0.61 with FFM for females and males, respectively.

The race-combined preliminary equations for TBW and FFM for males and females were more parsimonious than were the corresponding equations for whites only, and the RMSE values of the race-combined preliminary equations were not significantly different from those of the white-only equations. The cross-validation results of the preliminary race-combined TBW and FFM equations are presented in **Table 4**. There were few blacks in the cross-validation sample; therefore, the results are presented as a race-combined sample only. The TBW values for the RMSE were 3.6 L for males and 2.6 L for females. The average TBW for males was 44.5 L, resulting in a CV of 8%. The mean TBW for females was 32.9 L and the corresponding CV was also 8%. Although the RMSE value of the TBW equations was larger for males than for females, the precision was similar for each, ≈8%. The RMSE values for FFM were 3.7 kg for males and 2.8 kg for females. The mean FFM for males was 59.6 kg and for females was 44.0 kg. The corresponding CVs for the FFM equations were ≈6% for both sexes.

The pure errors from the cross-validation results are also presented in Table 4. When the selected race-combined prediction equations were applied to the cross-validation sample, the resulting pure errors of prediction were only slightly larger than the corresponding RMSE. The pure errors for the TBW and FFM equations were 4.2 L and 4.5 kg for males, respectively, and 3.2 L and 3.4 kg for females, respectively; the corresponding RMSE values were 3.6 L and 3.7 kg and 2.6 L and 2.8 kg, respectively (Table 4). The CVs were larger for the cross-validation sample than for the validation sample. The race-combined equations slightly overpredicted TBW by ≈0.7 and 0.6 L and FFM by ≈0.3 and 0.6 kg for males and females, respectively. For comparison purposes, the differences in the pure errors between race-combined equations and the white-only equations for TBW and FFM were not statistically significant with the F-ratio test ($P < 0.05$). These results indicate that when the preliminary equations in Table 4 are applied to independent samples, there should be little if any trend in the residuals, and the predictive errors should be approximately equivalent to the pure errors. This comparison illustrates that the performance of these TBW and FFM equations, when applied to an independent sample, should be similar to this level of performance.

Final prediction equations

The final race-combined prediction equations for TBW and FFM are presented in **Table 5**. The TBW equation for males used 712 participants (574 whites and 138 blacks) and that for females used 1089 participants (875 whites and 214 blacks). The final TBW equation for males had an R^2 of 0.84 and an RMSE of 3.8 L; the corresponding values for females were an R^2 of 0.79 and an RMSE of 2.6 L. Both equations had a CV of 8%.

These final equations were validated by the PRESS statistics for blacks and whites separately and for the total sample. The PRESS statistics indicated that, overall, the cross-validation performance of the TBW equations was excellent (Table 5). The PRESS statistics for the TBW equation for males were 3.7 L for

TABLE 4
Preliminary bioelectrical impedance analysis race-combined prediction equations for total body water (TBW) and fat-free mass (FFM) and pure error from cross-validation[1]

Group	Equation	R^2	RMSE	Mean residual	Pure error
Males (n = 515)	TBW = 0.87 + 0.43 stature^2/resistance + 0.20 weight	0.85	3.6 L	−0.7 L	4.2 L
Females (n = 775)	TBW = 3.27 + 0.45 × stature^2/resistance + 0.12 weight	0.78	2.6 L	−0.6 L	3.2 L
Males (n = 512)	FFM = −9.88 + 0.65 stature^2/resistance + 0.26 weight + 0.02 resistance	0.90	3.7 kg	−0.3 kg	4.5 kg
Females (n = 776)	FFM = −11.03 + 0.70 stature^2/resistance + 0.17 weight + 0.02 resistance	0.85	2.8 kg	−0.6 kg	3.4 kg

[1] TBW is in L, FFM is in kg, stature^2/resistance is in cm^2/Ω, and resistance is in Ω. RMSE, root mean square error.

TABLE 5
Final bioelectrical impedance analysis race-combined prediction equations for total body water (TBW) and fat-free mass (FFM)[1]

Group	Equation	Goodness of fit		PRESS statistic (PRESS residual)		
		R^2	RMSE	Black	White	Races combined
Males (n = 712)	TBW = 1.20 + 0.45 stature^2/resistance + 0.18 weight	0.84	3.8 L	3.9 (2.0) L	3.7 (−0.5) L	3.8 (≈0) L
Females (n = 1089)	TBW = 3.75 + 0.45 stature^2/resistance + 0.11 weight	0.79	2.6 L	2.9 (1.4) L	2.6 (−0.3) L	2.6 (≈0) L
Males (n = 669)	FFM = −10.68 + 0.65 stature^2/resistance + 0.26 weight + 0.02 resistance	0.90	3.9 kg	4.4 (2.1) kg	3.8 (−0.4) kg	3.9 (≈0) kg
Females (n = 944)	FFM = −9.53 + 0.69 stature^2/resistance + 0.17 weight + 0.02 resistance	0.83	2.9 kg	3.4 (1.6) kg	2.9 (−0.3) kg	2.9 (≈0) kg

[1] TBW is in L, FFM is in kg, stature^2/resistance is in cm^2/Ω, and resistance is in Ω. RMSE, root mean square error; PRESS, prediction of sum of squares.

whites, 3.9 L for blacks, and 3.8 L for both races combined; the corresponding values for females were 2.6, 2.9, and 2.6 L, respectively. However, with use of the PRESS residuals, there was a tendency to underpredict TBW in black males by ≈2.0 L and to overpredict TBW in white males by ≈0.5 L. Similarly, the final TBW equations for females also underpredicted TBW, by ≈1.4 L in black females, and overpredicted TBW by ≈0.3 L in white females.

The final FFM prediction equations included 669 male participants (552 whites and 117 blacks) and 944 female participants (785 whites and 159 blacks). The R^2 values were 0.90 for males and 0.83 for females. The corresponding values for RMSE were 3.9 kg for males and 2.9 kg for females. Both of these final FFM equations had a CV of 6%. The values for the PRESS statistics were similar to the RMSE values, indicating reasonable excellent performance of the FFM equations. As for TBW, the final FFM equations also tended to underpredict FFM in blacks and to overpredict FFM in whites. The corresponding values were ≈2.1 and ≈0.4 kg for black and white males and ≈1.6 and 0.3 kg for black and white females, respectively.

The performance of these final TBW and FFM prediction equations was examined graphically by plotting the predicted versus the observed values as well as the PRESS residuals versus predicted values for each sex and race separately. All the final equations had excellent precision. The predicted and observed values for TBW and FFM for males and females fell on or near the line of identity, and the residuals were randomly scattered on the narrow band around zero for TBW and FFM. Close agreement is shown between the predicted and observed values for TBW in **Figures 1–4** and for FFM in **Figures 5–8** for both males and females. The TBW and FFM equations performed well for white males. The regression line of the predicted versus observed values was close to the line of identity, except that there was some overprediction in the lower end and underprediction in the upper end of the distribution (Figures 1, 3, 5, and 7). There was no specific trend in the PRESS residuals when plotted with predicted values (Figures 1, 3, 5, and 7) but there was a slight systematic underprediction of TBW and FFM in blacks (Figures 2, 4, 6, and 8).

DISCUSSION

The purpose of this study was to develop broadly applicable prediction equations for TBW and FFM in a wide variety of white and black persons with normal body composition with the use of selected BIA and anthropometric measurements. BIA is a simple, easy-to-use method of estimating body composition in large-scale epidemiologic studies, and whole-body BIA measures at 50 kHz are frequently used in combination with anthropometry to predict body composition (13, 31, 32). The final race-combined prediction equations are to be applied to the BIA data from NHANES III for each subject aged 12–80 y so that TBW, FFM, TBF, and percentage body fat can be calculated.

NHANES III included participants with a broad range of body types, ages, racial-ethnic groups, and health conditions. Thus, it was necessary to develop the prediction equations from samples that are as representative of the population as possible. The final prediction equations were derived with the use of data from a large number of participants (734 males and 1095 females) representing a broad range of age and body sizes from 5 study sites. This combination of data from 5 separate samples shown in Table 1

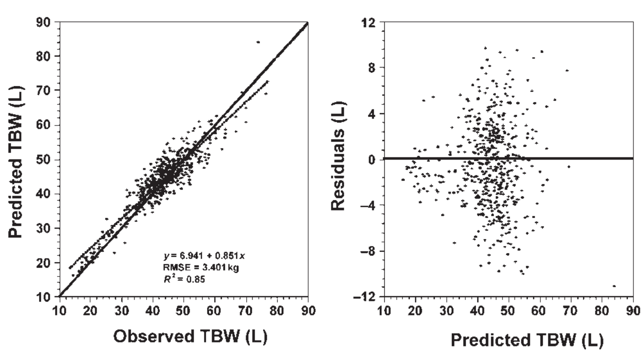

FIGURE 1. Predicted versus observed total body water (TBW), the line of identity, and the regression line of predicted and observed TBW and PRESS (prediction of sum of squares) residuals versus predicted TBW and the zero reference line in white males. RMSE, root mean square error.

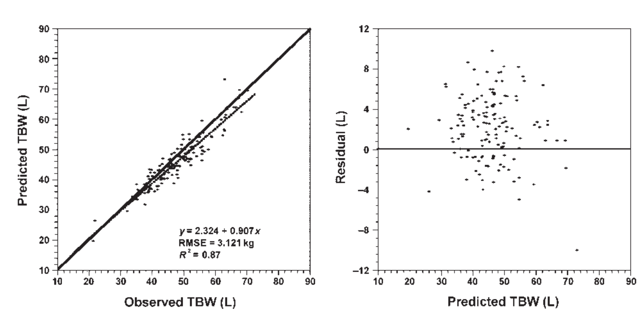

FIGURE 2. Predicted versus observed total body water (TBW), the line of identity, and the regression line of the predicted and observed TBW and PRESS (prediction of sum of squares) residuals versus predicted TBW and the zero reference line in black males. RMSE, root mean square error.

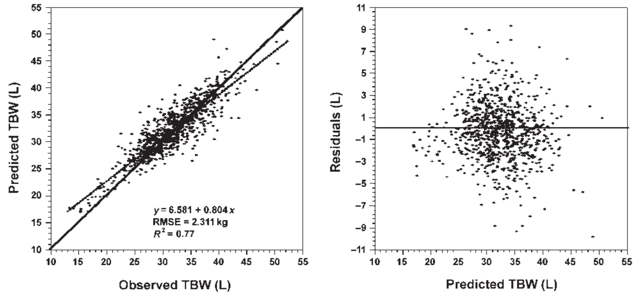

FIGURE 3. Predicted versus observed total body water (TBW), the line of identity, and the regression line of predicted and observed TBW and PRESS (prediction of sum of squares) residuals versus predicted TBW and the zero reference line in white females. RMSE, root mean square error.

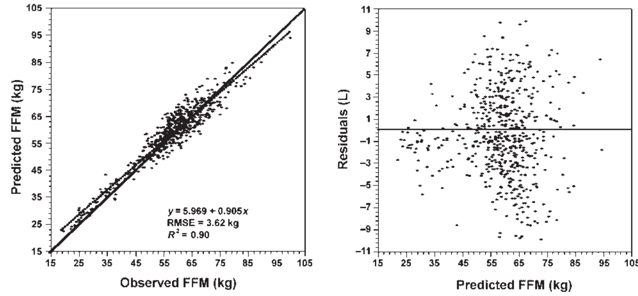

FIGURE 5. Predicted versus observed fat-free mass (FFM), the line of identity, and the regression line of the predicted and observed FFM and PRESS (prediction of sum of squares) residuals versus predicted FFM and the zero reference line in white males. RMSE, root mean square error.

increased the age, sex, and race distributions of the variables used (Table 2). The investigators at these sites have established long-term collaboration and interactions, and the data-collection protocols at the sites are very similar.

Variable selection and preliminary equation development

The selection of the variables used in the preliminary equations was based in part on their association with TBW and FFM. As shown in Table 3, of all the independent variables, stature^2/resistance had the highest R^2 and the lowest RMSE values with TBW and FFM. Preliminary prediction equations containing only anthropometric measures as independent variables were developed by the all-possible-subsets regression procedure as part of the total of 1024 developed equations. These "anthropometry only" prediction equations were not considered further in this analysis because these equations had smaller R^2 and larger RMSE and Cp values than did the BIA preliminary equations. The prediction equations with BIA values as independent variables had higher R^2 and smaller RMSE and Cp values than did those equations that contained anthropometry only.

The independent variables selected for the TBW prediction equations included stature^2/resistance and weight for both males and females (Table 4). The inclusion of these variables is not surprising because water is the most abundant compound in the body, making up ≈40–60% of body weight depending on the sex, race, and age of the person (4, 11). The independent variable stature^2/resistance is a major contributor in predicting TBW because the BIA current is conducted by the aqueous compartment of the body. The positive regression coefficients for body weight are the partial correlations after the consideration of stature^2/resistance.

The independent variables for the FFM equations included stature^2/resistance, weight, and resistance for males and females (Table 4). Compared with the TBW equations, the best FFM equations included resistance as an additional variable (Table 4). The measure of stature^2/resistance is an index of TBW that constitutes ≈73% of the FFM, although this percentage varies among persons (33). Inclusion of resistance in addition to weight and stature^2/resistance in the FFM prediction equations is an indication that stature^2/resistance may have undercorrected for resistance, which, in turn, exaggerated the conductivity of the FFM.

Final prediction equations

The regression analyses was repeated with use of the total available sample by using the variables selected in the preliminary equation development. The sample for the final equations included 712 males and 1089 females for TBW and 669 males and 944 females for FFM, all of whom were 12–94 y of age. The final BIA equations were developed with the use of both the black and white samples combined. With such a large number of participants, these final race-combined prediction equations were more robust when applied to an independent sample than were the preliminary equations developed with fewer participants. The final race-combined equations for TBW had a high R^2 value, and the RMSE values were 3.8 L for males and 2.6 L for females (Table 5). The final race-combined prediction equations for FFM also fit the data well. The R^2 values were 0.90 for males and 0.83

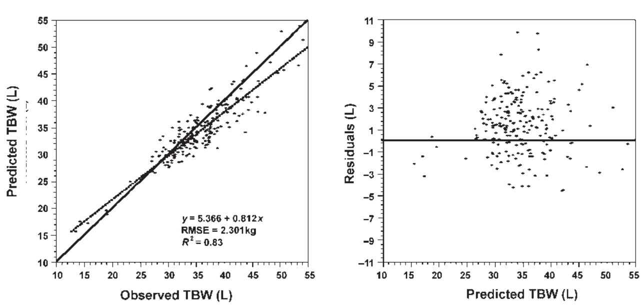

FIGURE 4. Predicted versus observed total body water (TBW), the line of identity, and the regression line of predicted and observed TBW and PRESS (prediction of sum of squares) residuals versus predicted TBW and the zero reference line in black females. RMSE, root mean square error.

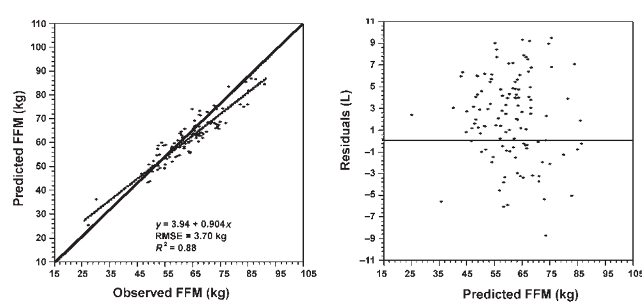

FIGURE 6. Predicted versus observed fat-free mass (FFM), the line of identity, and the regression line of the predicted and observed FFM and PRESS (prediction of sum of squares) residuals versus predicted FFM and the zero reference line in black males. RMSE, root mean square error.

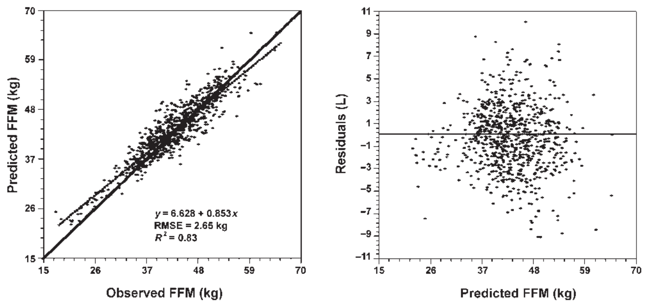

FIGURE 7. Predicted versus observed fat-free mass (FFM), the line of identity, and the regression line of the predicted and observed FFM and PRESS (prediction of sum of squares) residuals versus predicted FFM and zero reference line in white females. RMSE, root mean square error.

for females, and the corresponding RMSE values were 3.9 kg for males and 2.9 kg for females.

Most of the published BIA prediction equations are limited, due in part to a narrow age range and specificity to the racial makeup of their samples. Among the published equations, there are wide variations in the goodness-of-fit measure and RMSE for TBW and for FFM: the RMSE for TBW ranged from 1.3 to 8.7 L and for FFM it ranged from 1.1 to 4.6 kg (22, 29, 30, 33). In these published equations, the number of subjects, in general, was small except for the equations of Deurenberg et al (34) and Roubenoff (31). Also, most of the published equations were derived for whites only.

Most of the published prediction equations for FFM and body fat use body-composition measures from a 2-component model or DXA as the criterion measure, with a few exceptions (13, 32). There are several limitations of the 2-component and the DXA methods of determining lean and fat tissues. The 2-component model is most suited to young adult white males. The DXA algorithms for soft tissue assume a constant hydration of the FFM (ie, 73% of water in FFM), which is erroneous (33). The present final FFM prediction equations are possibly the first to use a multicomponent body-composition model with direct measures of body density from underwater weighing, BMC from DXA, and TBW from isotope dilution for children and adults.

The cross-validation results for the development of the TBW and FFM equations indicated pure errors of 4.0 L for males and 3.0 L for females and 4.5 kg for males and 3.4 kg for females (Table 4). To further validate the present final equations, the PRESS procedure was used (Table 5). The race-combined PRESS statistics were similar to the RMSE values for the TBW and FFM equations, and the mean PRESS residuals were approximately zero, indicating their overall excellent performance. The PRESS statistics were also calculated separately by race and were similar to the RMSE values of the final equations (Table 5). These mean PRESS residuals were also close to zero, except that in whites TBW was slightly overpredicted (by ≈0.3 L for males and by ≈0.5 L for females), and FFM was overpredicted (by ≈0.4 kg for males and by ≈0.3 kg for females).

These final BIA race-combined prediction equations did not perform as well in the blacks as in the whites. The PRESS statistics were only slightly higher than the race-combined RMSE values, but the mean PRESS residuals in the blacks indicated an underprediction of TBW by 2.0 L in males and by 1.4 L in females and an underprediction of FFM by 2.0 kg in males and by 1.6 kg in females. As a result of the systematic prediction bias in the blacks and because these equations were derived from predominantly white data, the equations are more valid for whites than for blacks. We attempted to include data for as many blacks as possible, but there have been too few body-composition studies that included blacks, Mexican-Americans, and other ethnic groups of the US population. However, we did use a multicomponent body-composition model to account for age, sex, and race differences in the density of FFM as much as was possible. Nevertheless, it appears that even with the application of a multicomponent model, for good biological reasons there were residual racial differences for BIA and weight-based predictions of TBW and FFM (35).

From our evaluation, we anticipate that when these final equations are applied, the means for sex- and age-specific groups should be close to the true values for whites, but underpredicted TBW and FFM for blacks because of a systematic prediction bias. Because the equations do not capture all the sources of variability in body composition, the SDs of the estimates from these equations will tend to be lower than the true SDs in the population. The random errors in the body-composition prediction will tend to attenuate the relations of body composition with risk factors for disease for both whites and blacks. The systematic bias of the predicted value for blacks could affect comparisons between blacks and whites. However the systematic bias should not affect multivariate relations for blacks if measurement error models are applied to correct for these biases (26).

The final race-combined equations for TBW and FFM provided reasonable prediction for persons at the extremes of the distribution, as can be seen from the plots of the PRESS residuals (Figures 1–8). The PRESS residuals appear to be randomly located about the horizontal line of zero. There is only a slight trend of overprediction at the lower end of the distribution and of underprediction at the upper end of the distributions. These problems were noted in previous studies and were attributed to the criterion method of underwater weighing (36). However, in the obese, in clinical cases, or in those groups with greater-than-normal amounts of adipose tissue, the errors of prediction from these equations will be exacerbated; thus, these equations are not applicable to such groups.

The present equations were developed with the use of data from children as young as 12 y of age. It is possible that the prediction for children may be compromised as a function of the differences in levels of maturation between children, specifically their level of sexual maturation. In the development of these equations, we assumed that the relations of TBW and FFM with the independent variables used were parallel for the various stages of sexual

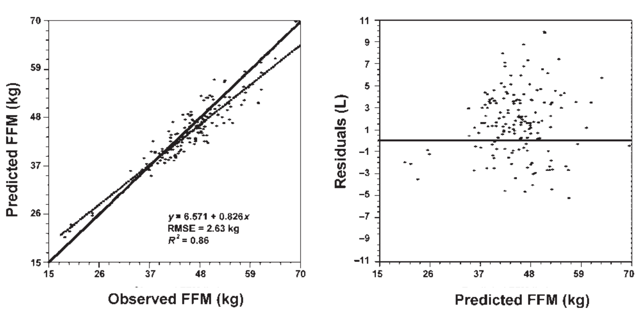

FIGURE 8. Predicted versus observed fat-free mass (FFM), the line of identity, and the regression line of the predicted and observed FFM and PRESS (prediction of sum of squares) residuals and predicted FFM and the zero reference line in black females. RMSE, root mean square error.

development among the children. When the final equations were applied to the children younger than 20 y of age, the R^2 and RMSE values were similar if only slightly better than the corresponding values for the total sample of subjects. However, the use of these equations with data from children between the age of 12 y and the age of maturity should be done cautiously because maturational development can vary greatly between children depending on their age and sex.

Conclusion

Two sets of prediction equations were validated and cross-validated for TBW and FFM by using 5 sets of BIA and body-composition data for males and females separately and for the races combined at all ages. There are recognized racial-ethnic differences in body composition; thus, it was likely that the equation that used data from whites only would perform less satisfactorily when applied to blacks than would the race-combined equations. The final sex-specific, age- and race-combined equations were selected as the most accurate and precise for predicting TBW and FFM. These findings indicate the utility of BIA in large-scale epidemiologic studies, for which more sophisticated body-composition methods are impractical because of their cost and the time involved.

The present BIA prediction equations have several advantages over published equations. The criterion methods for body composition were used in a multicomponent model that accounts for variations in bone, water, and fat. The final equations are derived from data from 5 study sites that constitute subjects with a wide age range, 2 races, and both sexes. The statistical procedure, all-possible-subsets regression analysis, evaluated every possible combination of the independent variables in the prediction of the dependent variables. This produces the best equations by allowing the simultaneous comparison among the set of possible equations. In conjunction with the Cp statistic, the minimum RMSE, and the significance of the regression estimates, the all-possible-subsets regression analysis ensures that the appropriate number of independent variables is included in the equation, and the criteria of the minimum RMSE and the significance of the regression estimates results in parsimonious equations. The equations are reasonably generalizable for groups with body-composition values at the extremes of the distribution, as assessed with the use of the PRESS procedure.

REFERENCES

1. Shephard RJ. Physical activity and reduction of health risks: how far are the benefits independent of fat loss? J Sports Med Phys Fitness 1994;34:91–8.
2. Hill GL, Jonathan E. Rhoads lecture. Body composition research: implications for the practice of clinical nutrition. JPEN J Parenter Enteral Nutr 1992;16:197–218.
3. Steen B. Body water in the elderly—a review. J Nutr Health Aging 1997;1:142–5.
4. Chumlea WC, Guo SS, Zeller CM, Reo NV, Siervogel RM. Total body water data for white adults 18 to 64 years of age: the Fels Longitudinal Study. Kidney Int 1999;56:244–52.
5. Schoeller DA. Changes in total body water with age. Am J Clin Nutr 1989;50(suppl):1176–81.
6. NHLBI. Obesity Education Initiative Expert Panel on the Clinical Guidelines on the Identification, Evaluation and Treatment of Overweight and Obesity in Adults: the evidence report. Obes Res 1998;6: 51S–209S.
7. Kuczmarski RJ, Flegal KM, Campbell SM, Johnson CL. Increasing prevalence of overweight among US adults. The National Health and Nutrition Examination Surveys, 1960 to 1991. JAMA 1994;272: 205–11.
8. Troiano RP, Flegal KM, Kuczmarski RJ. Overweight prevalence and trends for children and adolescents: The National Health and Nutrition Examination Surveys, 1963 to1991. Arch Pediatr Adolesc Med 1995;149:1085–91.
9. Ogden CL, Troiano RP, Briefel RR. Prevalence of overweight among preschool children in the United States, 1971–1994. Pediatrics [serial online] 1997;99:E1. Internet: http://www.pediatrics.org/cgi/content/full/99/4/E1 (accessed 16 October 2002).
10. Gallagher D, Visser M, Sepulveda D. How useful is body mass index for comparison of body fatness across age, sex, and ethnic groups? Am J Epidemiol 1993;22:228–39.
11. Lukaski HC. Methods for the assessment of human body composition: traditional and new. Am J Clin Nutr 1987;46:537–56.
12. Chumlea WC, Guo S. Bioelectrical impedance and body composition: present status and future directions. Nutr Rev 1994;52:123–31.
13. Guo S, Roche AF, Houtkooper LH. Fat-free mass in children and young adults from bioelectric impedance and anthropometry variables. Am J Clin Nutr 1989;50:435–43.
14. Guo SS, Chumlea WC. Statistical methods for the development and testing of predictive equations. In: Roche AF, Heymsfield SB, Lohman TG, eds. Human body composition: methods and findings. Champaign, IL: Human Kinetic Press, 1996:191–202.
15. Kushner R, Schoeller D. Estimation of total body water by bioelectrical impedance analysis. Am J Clin Nutr 1986;44:417–24.
16. Lukaski H, Johnson P, Bolonchuk W, Lykken G. Assessment of fat-free mass using bioelectrical impedance measurements of the human body. Am J Clin Nutr 1985;41:810–7.
17. Cordain L, Whicker R, Johnson J. Body composition determination in children using bioelectrical impedance. Growth Dev Aging 1988; 52:37–40.
18. Withers RT, Laforgia J, Heymsfield SB. Critical appraisal of the estimation of body composition via two-, three-, and four-compartment models. Am J Hum Biol 1999;11:175–85.
19. DHHS, Department of Health Statistics. NHANES III reference manuals and reports. Hyattsville, MD: National Center for Health Statistics, 1996 (CD-ROM).
20. National Institutes of Health. Bioelectrical impedance analysis in body composition measurement. Am J Clin Nutr 1996;64(suppl): 524S–32S.
21. Roche AF. Growth, maturation and body composition: the Fels Longitudinal Study 1929–1991. London: Cambridge University Press, 1992.
22. Friedl KE, DeLuca JP, Marchitelli LJ, Vogel JA. Reliability of body fat measurements from a four-compartment model using density, body water, and bone mineral measurements. Am J Clin Nutr 1992; 55:764–70.
23. Lohman T, Martorell R, Roche AF. Anthropometric standardization reference manual. Champaign, IL: Human Kinetics, 1988.
24. Schoeller DA. Hydrometry. In: Roche AF, Heymsfield SB, Lohman TG, eds. Human body composition: methods and findings. Champaign, IL: Human Kinetics, 1996:25–43.
25. Ma KJ, Wang J, Pierson RN Jr. Total body water (TBW) methods: tritium ($^3H_20$) and deuterium (D_20) spaces from plasma and saliva. FASEB J 1998;12:A868 (abstr).
26. Guo SS, Chumlea WC, Roche AF, Siervogel RM. Age- and maturity-related changes in body composition during adolescence into adulthood: the Fels Longitudinal Study. Int J Obes Relat Metab Disord 1997;21:1167–75.
27. Heymsfield SB, Wang ZM, Withers RT. Multicomponent molecular level models of body composition analysis. In: Roche AF, Heymsfield SB, Lohman TG, eds. Human body composition: methods and findings. Champaign, IL: Human Kinetics, 1996:129–48.

28. SAS II. SAS procedures guide. 6th ed. Cary, NC: SAS Institute Inc, 1990.
29. Myers RH. Classical and modern regression with applications. Boston: Duxbury, 1986.
30. Mallows CL. Some comments on Cp. Technometrics 1973;15:661–75.
31. Roubenoff R. Applications of bioelectrical impedance analysis for body composition to epidemiologic studies. Am J Clin Nutr 1996; 64(suppl):459S–62S.
32. Houtkooper L, Going S, Lohman T, Roche A, Van Loan M. Bioelectrical impedance estimation of fat-free body mass in children and youth: a cross-validation study. J Appl Physiol 1992;72:366–73.
33. Siri W. Body composition from fluid spaces and density analysis of methods. In: Brozek J, Henschel A, eds. Techniques for measuring body composition. Washington, DC: National Academy Press, 1961: 223–44.
34. Deurenberg P, Vanderkooy K, Leenen R, Weststrate J, Seidell J. Sex and age specific prediction formulas for estimating body composition from bioelectrical impedance—a cross-validation study. Int J Obes Relat Metab Disord 1991;15:17–25.
35. Schoeller DA, Luke A. Bioelectrical impedance analysis prediction equations differ between African Americans and Caucasians, but it is not clear why. Ann N Y Acad Sci 2000;904:225–6.
36. Hodgdon JA, Fitzgerald PI. Validity of impedance predictions at various levels of fatness. Hum Biol 1987;59:281–98.