Validation of tetrapolar bioelectrical impedance method to assess human body composition

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LUKASKI, HENRY C., WILLIAM W. BOLONCHUK, CLINT B. HALL, AND WILLIAM A. SIDERS. *Validation of tetrapolar bioelectrical impedance method to assess human body composition.* J. Appl. Physiol. 60(4):1327–1332, 1986.—This study was conducted to validate the relationship between bioelectrical conductance (ht^2/R) and densitometrically determined fat-free mass, and to compare the prediction errors of body fatness derived from the tetrapolar impedance method and skinfold thicknesses, relative to hydrodensitometry. One-hundred and fourteen male and female subjects, aged 18–50 yr, with a wide range of fat-free mass (34–96 kg) and percent body fat (4–41%), participated. For males, densitometrically determined fat-free mass was correlated highly ($r = 0.979$), with fat-free mass predicted from tetrapolar conductance measures using an equation developed for males in a previous study. For females, the correlation between measured fat-free mass and values predicted from the combined (previous and present male data) equation for men also was strong ($r = 0.954$). The regression coefficients in the male and female regression equations were not significantly different. Relative to hydrodensitometry, the impedance method had a lower predictive error or standard error of the estimates of estimating body fatness than did a standard anthropometric technique (2.7 vs. 3.9%). Therefore this study establishes the validity and reliability of the tetrapolar impedance method for use in assessment of body composition in healthy humans.

fat-free mass; percent body fat; densitometry; anthropometry

ALTHOUGH THE IMPORTANCE of assessing human body composition in physiological and nutritional research has been established, the routine use of body compositional methods is limited by practical constraints. Laboratory methods such as densitometry (1), computed tomography (3), electrical conductivity (22, 25), body water by isotope dilution (13, 24), whole-body counting of potassium-40 (5), and neutron activation analysis for total body calcium and N_2 (6, 29) are expensive and are not suited for field studies. Other techniques developed for epidemiological surveys, such as anthropometry (2), skinfold thickness measures (9), and infrared interactance (7) are less reliable predictors of body composition. Thus there is a need for a safe, noninvasive technique that is rapid and convenient and provides reliable and sufficiently accurate estimates of human body composition outside the laboratory. Measurement of whole-body bioelectrical impedance is an approach that may meet this need.

The method for determining body impedance is based on the conduction of an applied electrical current in the organism. In biological structures, application of a constant low-level alternating current results in an impedance to the spread of the current that is frequency dependent. The living organism contains intra- and extracellular fluids that behave as electrical conductors and cell membranes that act as electrical condensors and are regarded as imperfect reactive elements. At low frequencies (~1 kHz) the current mainly passes through the extracellular fluids, whereas at higher frequencies (500–800 kHz), it penetrates the intra- and extracellular fluids (18). Thus body fluids and electrolytes are responsible for electrical conductance (e.g., $1/R$), and cell membranes are involved in capacitance.

Bioelectrical impedance measurements have been related to biological function such as pulsatile blood flow (17) and to determination of total body water in healthy and diseased individuals (10, 15, 22). Utilizing the fact that fat-free mass has a much greater conductivity than does fat (21), we established a strong relationship between conductance and fat-free mass in healthy males (15).

We report here the results of a study designed to crossvalidate our original relationship between conductance and densitometrically determined fat-free mass and percent body fat in independent samples of men and women, and to compare the accuracy of body composition estimates from skinfold thickness measurements and the electrical impedance method relative to densitometry.

MATERIALS AND METHODS

The hypothesis that bioelectrical impedance measurements can be used to determine fat-free mass is based on the principle that the impedance of a geometrical system is related to conductor length and configuration, its cross-sectional area, and signal frequency. With a constant signal frequency and a relatively constant conductor configuration, bioelectrical impedance to the flow of current can be related to the volume of the conductor: $Z = \rho L/A$, where Z is impedance in ohms, ρ is volume resistivity in $\Omega \cdot cm$, L is conductor length in centimeters, and A is conductor cross-sectional area in centimeters squared. Multiplying both sides of the equation by L/L gives: $Z = \rho L^2/AL$, where AL is equal to volume (V).

Substituting gives, $Z = \rho L^2/V$.

In biological systems, electrical conduction is related to water and ionic distribution in the conductor. Because fat-free mass, which includes the protein matrix of adipose tissue, contains virtually all the water and conducting electrolytes in the body, conductivity is far greater in the fat-free mass than the fat mass of the body (21). This hypothetical relationship was proposed by Nyboer et al. (19), who demonstrated that electrically determined biological volumes were inversely related to Z, resistance (R), and reactance (Xc).[1] Because the magnitude of reactance is small relative to resistance, and resistance is a better predictor of impedance than is reactance (10, 15), then the expression for V becomes: $V = \rho L^2/R$, where R is in ohms.

Although there are difficulties in applying this general principle in a system with complex geometry and bioelectrical characteristics as the healthy human body, we (15) and others (10, 20, 25) have utilized this empirical relationship to develop models relating conductance (ht^2/R) to fat-free mass, total body water, and potassium.

Subjects. One hundred-fourteen healthy men and women aged 19–50 yr volunteered to participate in this study. To control for electrolyte retention and water accumulation, each female underwent all procedures 7–8 days after the start of her menstrual period. Each volunteer gave written informed consent after receiving a detailed description of the purpose and procedures of this investigation. All experimental procedures were approved by the Institutional Review Boards of the United States Department of Agriculture and the University of North Dakota School of Medicine. Each volunteer completed all tests on the same day ~2 h after consuming a light breakfast.

Densitometry. Body density was determined from hydrostatic weighing using the system and procedures of Akers and Buskirk (1), with the modification that the strain gauges are mounted under the water. Residual volume was measured simultaneously with the underwater weighing by an open-circuit technique for N_2 washout of the lungs (8). Percent body fat (%BF) was calculated from body density (D_b) according to Brozek et al. (4), $\%BF = 100\ [(4.570/D_b)-4.142]$. Fat-free mass was calculated as the difference between body mass and fat mass, where fat mass equaled body mass times percent body fat. With this system, percent body fat can be estimated with a precision of less than 1%, which is a value similar to the precision reported by others using this method and apparatus (1, 16).

Bioelectrical impedance. Determinations of resistance and reactance were made using a four-terminal impedance plethysmograph[2] (RJL Systems, model 101, Detroit, MI). The tetrapolar method was used to minimize contact impedance or skin-electrode interaction (10, 17). Measurements were made ~2 h after eating and within 30 min after voiding. Each volunteer, clothed but without shoes or socks, was supine in the horizontal position on a cot. Aluminum foil spot electrodes (Contact Products, no. M6001, Dallas, TX) were positioned in the middle of the dorsal surfaces of the hands and feet proximal to the metacarpal-phalangeal and metatarsal-phalangeal joints, respectively, and also medially between the distal prominences of the radius and the ulna and between the medial and lateral malleoli at the ankle. Specifically the proximal edge of one detector electrode was in line with the proximal edge of the ulnar tubercle at the wrist, and the proximal edge of the other detecting electrode was in line with the medial malleolus of the ankle. The current-introducing electrodes are placed a minimum distance of the diameter of the wrist or ankle beyond the paired detector electrode. A thin layer of electrolyte gel was applied to each electrode before application to the skin. An excitation current of 800 μA at 50 kHz was introduced into the volunteer at the distal electrodes of the hand and foot, and the voltage drop was detected by the proximal electrodes.[3] Use of this electrical current provides a deep homogenous electrical field in the variable conductor of the human body. Measurements of resistance and reactance were made using electrodes placed on the ipsilateral and contralateral sides of the body. Based on the results of Hoffer et al. (10), who found a strong inverse relationship between impedance and body water, and our previous study (15) showing a strong inverse correlation between resistance, taken as the lowest resistance value from all transmission axes and fat-free mass, we have used the lowest observed resistance value as representative of an individual to predict the body composition of that volunteer.

Anthropometry. Standing height, without shoes or socks, was measured to the nearest 0.1 cm with a stadiometer (Harpenden, Pembrokeshire, England) mounted on a wall. Body mass was determined on a calibrated scale (Toledo Scale, model 2831, Worthington, OH) accurate to ±0.2 kg.

Skinfold thicknesses were measured to 0.1 mm at the triceps, biceps, suprailiac crest, and scapula on the right side of the body using a Tanner-Whitehouse skinfold caliper (Harpenden, Pembrokeshire, England) calibrated to exert a constant pressure of 10 g/mm^2. Density was derived from the sum of these four skinfold thicknesses, using the equations of Durnin and Womersley (9). To be consistent with the body composition estimates derived from hydrodensitometry, percent body fat was calculated from density values using the Brozek formula (4). The precision of this method is reported to be 3.5% body fat (13).

Statistical analyses. A double crossvalidation (11) of the prediction of fat-free mass from conductance measures was performed using data from both the present and previous study (15), in which densitometrically determined fat-free mass (range: 44–98 kg) and impedance measures were obtained in 37 healthy men aged 19–42 yr. This analysis was also used on the percent body fat

[1] $Z = \sqrt{R^2 + Xc^2}$

[2] Mention of a trademark or proprietary product does not constitute a guarantee or warranty by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products that may also be suitable.

[3] According to Ohm's law, the electrical impedance (Z) to alternating current of a circuit is measured in terms of voltage (E) and current (I) as $Z = E/I$. By using phase-sensitive electronics, one can quantitate the geometrical components of Z; resistance (R) is the sum of in-phase vectors, and reactance (Xc) is the sum of out-of-phase vectors.

data derived from the observed and predicted fat-free mass values.

Multiple regression analyses were applied to identify the best predictors of fat-free mass. The regressions were conducted in a stepwise manner (23), using the independent variables of height, body mass, age, gender, and impedance measures.

Multiple regression analysis and analysis of variance were used to simultaneously determine the equality of regression slopes and of intercepts for the relationships between fat-free mass and conductance between the previous (15) and present studies, and between men and women. This approach uses dummy variables (e.g., male = 1, female = 0) to test for separate regression lines according to Kleinbaum and Kupper (12).

Comparisons of Pearson product moment correlation coefficients were made using the Z transformation (26). The 0.05 level of significance was used in all statistical analyses.

RESULTS

The physical characteristics of the volunteers are summarized in Table 1. A wide range in age, fat-free mass, and impedance components was found. On the average, the men were taller, leaner, and weighed more than the women participants. Also the mean resistance values were lower, indicating greater average fat-free mass in the males (15).

Crossvalidation of the impedance method. The double crossvalidation of the impedance method in men was based on a previously developed linear regression equation that utilized ht^2/R to predict fat-free mass (15). A new equation was formulated using the data in the present study (Table 2*A*). The correlation coefficients relating ht^2/R to fat-free mass in these samples of men were similar ($P > 0.05$). When the equation from the previous study was used to predict fat-free mass from the conductance data in the present study (and vice versa), there was no change in the magnitude of the computed correlation coefficients (Table 2*B*). Similarly, correlation coefficients relating percent body fat derived from fat-free mass data (densitometrically determined and predicted from individual linear regression lines) were similar in both groups of men. Crossvalidation of percent body fat values found no change in the magnitude of the observed correlation coefficients.

TABLE 1. *Volunteer characteristics*

	Men (n = 47)		Women (n = 67)	
	Means ± SD	Range	Means ± SD	Range
Age, yr	26.9±8.0	18–50	27.0±6.4	19–43
Height, cm	182.4±9.1	165.1–201.4	166.3±8.3	147.6–192.0
Weight, kg	86.0±16.4	55.6–123.8	61.8±10.4	42.6–103.9
Fat-free mass, kg	71.5±12.0	50.5–96.3	46.0±6.7	34.4–62.0
Body fat, %	16.2±7.0	3.8–33.2	25.1±6.6	12.5–40.4
Resistance, Ω	432.4±59.2	310–576	559.7±51.3	458–691
Reactance, Ω	60.4±7.4	46–84	64.9±8.9	47–92
Phase angle,† degree	8.2±1.1	6.7–12.9	6.7±0.9	4.6–10.9

$P < 0.001$ difference between men and women. Phase angle, degrees = arc tan (reactance/resistance).

TABLE 2. *Double crossvalidation of impedance method against densitometrically determined fat-free mass in two independent samples of men*

	Previous Study n = 37 men	Present Study n = 47 men
A		
Ht^2/R	0.851±0.03	0.810±0.03
Intercept	3.04±2.03	6.39±2.07
Fat-free mass	$r_{yx} = 0.984$	$r_{yx} = 0.979$
	SEE = 2.51 kg	SEE = 2.50 kg
%Body fat	$r_{\hat{y}y} = 0.949$	$r_{\hat{y}y} = 0.911$
	SEE = 2.38%	SEE = 2.91%
B		
Fat-free mass	$r_{\hat{y}y} = 0.984$	$r_{\hat{y}y} = 0.979$
	SEE = 2.51 kg	SEE = 2.50 kg
%Body fat	$r_{\hat{y}y} = 0.949$	$r_{\hat{y}y} = 0.910$
	SEE = 2.38%	SEE = 2.96%

Values for ht^2/resistance (R) and intercept are regression coefficients ± SD. *A*, best-fitting equation for predicting fat-free mass; *B*, correlation of fat-free mass from densitometry with fat-free mass predicted by impedance (predicted by applying equation developed in previous study, and vice versa); SEE, standard error of estimate; r_{xy}, correlation coefficient calculated between fat-free mass and ht^2/R; $r_{\hat{y}y}$, correlation coefficient calculated between predicted and measured values. * Predicted by applying equation developed in previous study and vice versa.

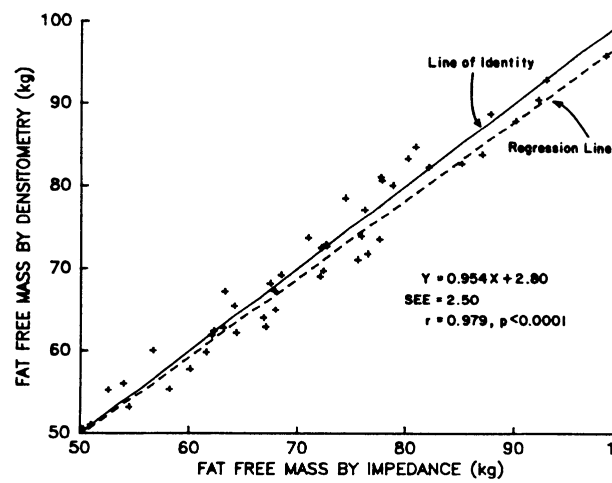

FIG. 1. Relationship between fat-free mass predicted from a previously developed regression equation for men (15) and densitometrically determined fat-free mass in 47 men.

Statistical analyses found no significant difference between either the slopes or the intercepts of the individual regression lines for the independent samples of men. This indicates the validity and reliability of ht^2/R as a predictor of fat-free mass in healthy men.

For males, the relationship between fat-free mass determined by hydrodensitometry and predicted by the equation derived in the previous study and applied to the conductance data of the present study is shown in Fig. 1. The regression coefficients of this line indicate that the slope is not significantly different (F = 2.04, P = 0.23) than one, and the intercept is no different (P = 0.94) than 0. Therefore the plotted line is not significantly different than the line of identity.

The results of the validation procedure comparing the impedance method in men from the previous and present studies on women are presented in Table 3. Correlation coefficients relating ht^2/R to densitometrically deter-

TABLE 3. *Double crossvalidation of impedance method against densitometrically determined fat-free mass in men and women*

	Men (n = 84)	Women (n = 67)
A		
Ht^2/R	0.827±0.018	0.821±0.032
Intercept	5.214±1.436	4.917±1.632
Fat-free mass	r_{yx} = 0.981 SEE = 2.51 kg	r_{yx} = 0.953 SEE = 1.99 kg
%Body fat	$r_{\hat{y}y}$ = 0.933 SEE = 2.70%	$r_{\hat{y}y}$ = 0.882 SEE = 3.13%
B		
Fat-free mass	$r_{\hat{y}y}$ = 0.981 SEE = 2.51 kg	$r_{\hat{y}y}$ = 0.953 SEE = 2.02 kg
%Body fat	$r_{\hat{y}y}$ = 0.932 SEE = 2.70%	$r_{\hat{y}y}$ = 0.882 SEE = 3.14%

Values for ht²/resistance (R) and intercept are regression coefficients ± SD. *A*, best-fitting equation for predicting fat-free mass; *B*, correlation of fat-free mass from densitometry with fat-free mass predicted by impedance (predicted by applying equation developed for men and vice versa); r_{yx}, correlation coefficient calculated between fat-free mass and ht^2/R; SEE, standard error of estimate; $r_{\hat{y}y}$, correlation coefficient calculated between predicted and measured values.

mined fat-free mass were similar in the male and female samples. Also the magnitude of these coefficients was unchanged when they were calculated by comparing the observed and predicted fat-free mass values using the double crossvalidation procedure (Table 3*B*). Similarly the correlation coefficients relating observed and predicted percent body fat in each sample were not significantly different, and the magnitude of these coefficients derived from the crossvalidation procedure was not changed.

No statistical difference (F = 0.609; F 0.05; 2,147 = 3.06) was found between either the slopes or the intercepts of the regression lines relating ht^2/R to fat-free mass of the male and female volunteers (Table 3). The similarity of regression coefficients across gender groups establishes the validity of this relationship.

For the women studied, the relationship between fat-free mass, determined by underwater weighing and predicted from the ht^2/R data using the regression coefficients derived from the male data (Table 3*A*), is shown in Fig. 2. The regression line was no different from the line of identity; the slope was no different ($F = 0.04$, $P = 0.85$) than 1, and the intercept was similar ($P = 0.89$) to 0. This observation extends the validity and reliability of the variable ht^2/R as a predictor of fat-free mass.

Statistical tests (12) did not find a significant interaction between gender and ht^2/R. This finding is consistent with the previous observation that the regression coefficients relating fat-free mass and conductance values were similar in the male and female samples.

Results of the stepwise regression analyses identified some significant predictors of fat-free mass among all volunteers (Table 4). The best single predictor was ht^2/R. Addition of body mass and reactance variables to the prediction equation reduced the standard error of estimates (SEE) of the estimated fat-free mass, and marginally improved the R^2 by 0.005.

Figure 3 presents the regression line developed to

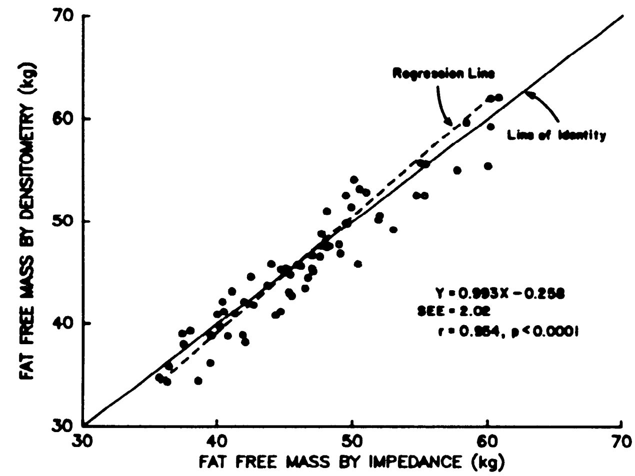

FIG. 2. Relationship between fat-free mass predicted from an equation developed for men (previous and present study) and densitometrically determined fat-free mass in 64 women.

TABLE 4. *Multiple regression equations for predicting fat-free mass by densitometry from impedance measures in men and women*

	Predictors	R^2	SEE	P
X_1	Ht^2/R	0.979	2.30	<0.0001
X_2	Body mass	0.981	2.20	<0.0001
X_3	Reactance	0.984	2.06	<0.0001

Fat-free mass, kg = 0.756 X_1 + 0.110 X_2 + 0.107 X_3 − 5.463. R, resistance; SEE, reactance.

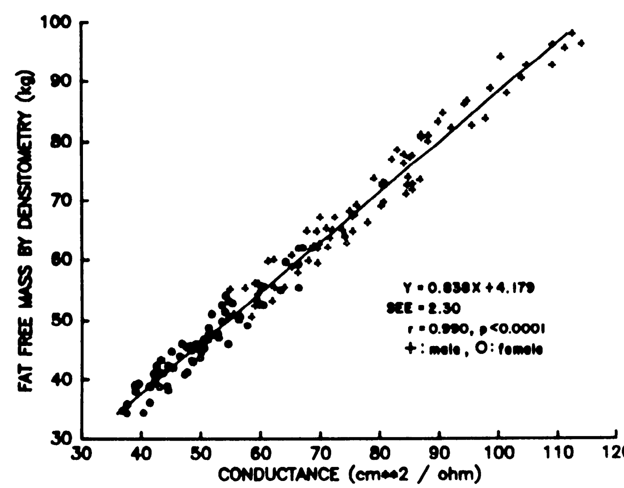

FIG. 3. Relationship between bioelectrical conductance and densitometrically determined fat-free mass in 151 men and women.

TABLE 5. *Accuracy of body composition methods for estimating percent body fat determined by hydrodensitometry*

Method	%Body fat	r_{yy}	SEE, %fat
Densitometry	21.1±7.9		
Impedance	21.0±8.3	0.928	2.66
Anthropometry	19.3±6.9	0.877	3.89

Calculated from skinfold thicknesses according to Durnin and Womersley (9). Significance is $P < 0.05$.

predict fat-free mass from conductance measures in healthy men and women.

Estimates of the predictive accuracy of the anthropometric and impedance methods in relation to hydrodensitometry are shown in Table 5. In conjunction with body-mass data, predictions of fat-free mass values derived by anthropometry and impedance were used to calculate percent body fat values that were regressed individually against densitometrically determined percent fat variables. The correlation coefficient relating anthropometric and densitometric estimates of body fat was significantly ($P < 0.05$) lower than the correlation coefficient calculated from the impedance method and hydrodensitometry. This is consistent with the greater SEE of percent body fat prediction with the anthropometry in comparison to impedance.

DISCUSSION

The use of bioelectrical impedance methodology to assess conductive volume is not new (for review see Ref. 17). The early results of Thomasett (27, 28), using bipolar subcutaneous electrodes, and of Hoffer et al. (10), using tetrapolar methods to determine total body water in humans, led Nyboer et al. (20) to conduct a pilot study to relate impedance measures to body composition in undergraduate men and women. Using densitometric data, but lacking accurate residual volume determinations, these investigators developed preliminary statistical relationships between conductance and body composition. However, Segal et al. (25) attempted to verify these regression equations and found unsatisfactory predictions of fat-free mass in men and women aged 18–50 yr. Recently, we have utilized standard methods to establish models to predict total body water and potassium and fat-free mass by the tetrapolar impedance method (15).

The results of the present study confirm our previous findings that conductance is a valid and reliable predictor of fat-free mass and the validity of this relationship is extended to women. The double cross-validation method (11) has shown nearly identical correlation coefficients and similar errors of predicting body compositional variables when regression equations, derived from independent samples, were used to estimate body components in men and women.

The use of any indirect method of assessing human body composition results in errors of prediction. Densitometry, the traditional reference method of body composition assessment, has a reported error of 2.5% in predicting body fat (13). As a predictor of densitometrically determined percent body fat, anthropometry can give an error of 3–9% (13). In comparison to densitometrically determined percent body fat, we found that the impedance method has an error of ~2.7%, and anthropometry has an error of ~3.9%. The lower error with the impedance method emphasizes a major difference between these methods; anthropometry relies on regional measurements to estimate whole-body composition, whereas densitometry and the impedance method utilize measurements of the whole body.

The similarity of the magnitude of the errors in predicting percent body fat for densitometry and the impedance method is encouraging, particularly because of the heterogeneous nature of the sample studied. This observation suggests that the impedance method may provide meaningful estimates of body composition in surveys of healthy populations.

It should be realized that the development of a new method of assessing human body composition is hampered by the lack of an accurate in vivo reference method. All techniques suffer from technical and biological errors. Although investigators can control technical errors, biological errors (e.g., interindividual deviations from basic assumptions such as the absolute constancy of the chemical composition of the fat-free mass) are present. Such departures can be minimized if methods are established and used in well-defined population groups.

The results of the present study have shown that the tetrapolar impedance method is valid and reliable, and it could be useful in field assessment of body composition among healthy people under steady-state conditions. It should be emphasized that additional research is necessary to establish the sensitivity of this method to quantitate change in fat-free mass as could be seen with physical training, weight loss or gain, and illness.

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