Assessment of fat-free mass using bioelectrical impedance measurements of the human body[1,2]

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ABSTRACT A method which involves the measurement of bioelectrical resistive impedance (R) for the estimation of human body composition is described. This method is based upon the principle that the electrical conductivity of the fat-free tissue mass (FFM) is far greater than that of fat. Determinations of R were made in 37 healthy men aged 28.8 ± 7.1 yr (mean ± SD) using an electrical impedance plethysmograph with a four electrode arrangement that introduces a painless signal (800 μA at 50 kHz) into the body. FFM was assessed by hydrodensitometry and ranged from 44.6–98.1 kg. Total body water (TBW) determined by D_2O dilution and total body potassium (TBK) from whole body counting were 50.6 ± 10.3 L and 167.5 ± 38.1 g, respectively. Test-retest correlation coefficient was 0.99 for a single R measurement and the reliability coefficient for a single R measurement over 5 days was 0.99. Linear relationships were found between R values and FFM ($r = -0.86$), TBW ($r = -0.86$), and TBK ($r = -0.79$). Significant ($p < 0.01$) increases in the correlation coefficients were observed when the predictor Ht^2/R was regressed against FFM ($r = 0.98$), TBW ($r = 0.95$), and TBK ($r = 0.96$). These data indicate that the bioelectrical impedance technique is a reliable and valid approach for the estimation of human body composition. This method is safe, noninvasive, provides rapid measurements, requires little operator skill and subject cooperation, and is portable. Further validation of this method is recommended in subjects with abnormal body composition. *Am J Clin Nutr* 1985;41:810–817.

KEY WORDS Human body composition, nutritional assessment, whole body impedance, fat-free mass, total body water, total body potassium

Introduction

Assessment of human body composition is an important factor in determining the nutritional status of an individual and of populations. Although a variety of body composition methods is available, the majority are limited to the research or clinical laboratory and include densitometry (1), determination of total body water (TBW; 2), potassium (TBK; 3), nitrogen (4), and calcium (5), tomography (6), and electrical conductivity (7). Other techniques that have been developed for field use, such as skinfold thickness (8) and ultrasound (9), are less reliable predictors of total body fat. Thus, there is a need for a technique that provides reliable and valid estimates of human body composition, is noninvasive, and is suitable for use outside of the laboratory. Measurement of whole body bioelectrical impedance is a approach that may meet this need.

The method for determining body impedance is based upon 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 consists of intra- and extracellular fluids that behave as electrical conductors, and cell membranes that act as electrical condensors and are regarded as imperfect reactive ele-

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ments. At low frequencies (~1 kHz), the current passes mainly through the extracellular fluid while at higher frequencies (500–800 kHz) it passes through the extra- and intracellular fluids (10, 11). In this manner, body fluids and electrolytes are responsible for electrical conduction (eg, 1/resistance) and cell membranes are involved in capacitance.

In the United States, the pioneering work of relating electrical impedance measurements to biological function was conducted by Nyboer who studied arterial pulse waveforms and pulsatile blood flow to organs using electrical impedance plethysmography (for review see 12). Thomasset (10, 11) conducted the original studies using electrical impedance measurements as an index of TBW. Later, Hoffer et al (13) defined a relationship between total body impedance and TBW. Since these early studies, there have been no attempts to determine the usefulness of the impedance method as a tool for evaluating human body composition.

The purpose of this study was to develop a method to use bioelectrical impedance measurements for assessing FFM, to determine the reliability of impedance measures, and to investigate the validity of these measurements by comparison with standard estimates and indices of human body composition.

Methods

The hypothesis that bioelectrical impedance measurements can be used to determine TBW is based upon the principle that the impedance of a geometrical system is related to conductor length and configuration, its cross-sectional area, and signal frequency. Using 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:

$$Z = \rho L/A \quad (1)$$

where Z is in ohm, ρ is volume resistivity in ohm-cm, L is conductor length in cm, and A is conductor cross-sectional area in cm^2. Multiplying equation 1 by L/L yields:

$$Z = \rho L^2/AL \quad (2)$$

where AL is equal to volume (V). Substituting gives:

$$Z = \rho L^2/V \quad (3)$$

In biological systems, electrical conduction is related to water and ionic distribution in the conductor. Because FFM, which includes the protein matrix of adipose tissue, contains virtually all the water and conducting electrolytes in the body, conductivity is far greater in FFM than FM (14). Equation 3 was proposed by Nyboer et al (15) who first demonstrated that electrically determined biological volumes were inversely related to impedance[3] (Z), resistance (R), and reactance (Xc). If it is hypothesized that the magnitude of Xc is small relative to R, and R is a better predictor of Z than is Xc, then the expression for V becomes:

$$V = \rho L^2/R \quad (4)$$

where R is in ohm.

Although there are difficulties in applying this general principle in a system with complex geometry and bioelectrical characteristics as the healthy human body, these equations have been developed as a general background for the empirical relationships to be presented subsequently.

Thirty-seven apparently healthy men volunteered to participate in this study. Each subject gave written informed consent after receiving a detailed description of the purpose and procedures of this investigation. This study was approved by the Human Studies Committees of the University of North Dakota School of Medicine and of the USDA Agricultural Research Service.

The men came to the laboratory on two consecutive days. On the first day, after an overnight fast, the volunteers reported for determination of TBW. Each man emptied his bladder, had a 10 ml venous blood sample drawn, then drank 10 g of 99.7% D_2O (Prochem Isotopes, Summit, NJ[4]) mixed with deionized water. After a 2-3 h equilibration period during which time no food or drink was consumed and all urine was collected, a 10 ml venous blood sample was drawn and the plasma was extracted. Plasma water was collected by vacuum sublimation and HOD concentrations were determined in triplicate by infrared absorption (16). TBW was calculated from the D_2O dose administered, corrected for urinary deuterium loss, and the observed deuterium concentration in the plasma water. The precision of TBW values determined by this method is 2.5% (16).

On the next morning, subjects reported to the laboratory after consuming a light breakfast. Body composition was determined by hydrodensitometry using the underwater weighing system and the method of Akers and Buskirk (17) with the modification that the strain gauges are mounted under water in the tank. Residual volume was measured simultaneously with the underwater weighing by an open circuit technique for nitrogen washout of the lungs (18). Percent body fat (%BF) was calculated from D_b according to Brozek et al (1).

$$\%BF = 100[(4.570/D_b) - 4.142] \quad (5)$$

FM and FFM were calculated from %BF and body mass (BM) as follows:

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

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

$$FM = \%BF(BM)/100 \quad (6)$$

$$FFM = BM - FM \quad (7)$$

where BM, FM, and FFM are in kg. Using this system, FM can be estimated with a precision of less than 1% BF, which is a value similar to the precision reported by others using this method (17, 19).

The TBK content of each volunteer was measured externally by detection of 1.46 Mev gamma rays emitted from the naturally occurring radioisotope ^{40}K which is a constant fraction (0.012%) of body potassium. The Grand Forks Human Nutrition Research Center whole-body counter with its on-line computer facility was used to quantitate absolute levels of TBK using the method of Cohn (20) to correct for individual differences in body geometry and gamma ray self-absorption. This counter includes an array of 16 high resolution 11×41 cm rectangular NaI T1-activated detectors above and below the subject who lies supine on a cot. Before the whole body count, each subject showered and washed his hair, then put on a clean scrub suit to avoid the interference of environmental radon which has been shown to erroneously increase apparent TBK levels (21). The precision for measuring TBK is 3%.

Determinations of R and Xc were made using a four terminal impedance plethysmograph (RJL Systems, Detroit, MI). The four electrode method was used to minimize contact impedance or skin-electrode interaction (13). The measurements were made about 2 h after eating and within 30 min after voiding. Each subject wore clothes, but no shoes or socks, and was supine on a cot. After cleaning all skin contact areas with alcohol, aluminum foil spot electrodes were placed on the dorsal surfaces of the hands and feet at the distal metacarpals and metatarsals, respectively, and also between the distal prominences of the radius and the ulna and between the medial and lateral malleoli at the ankle as shown in **Figure 1.** A thin layer of electrolyte gel was applied to each electrode before application to the skin. An excitation current (I) of 800 μA at 50 kHz was introduced into the subject at the distal electrodes of the hand and foot and the voltage drop (E) was detected by the proximal electrodes.[5] Use of this electrical current provides a deep homogenous electrical field in the variable conductor of the human body. Measurements of R and Xc were made using electrodes placed on the ipsilateral and contralateral sides of the body.

Reliability of impedance measurements was assessed by making repeated impedance determinations on successive days in a subsample of men.

One-factor analysis of variance using the repeated-measure design (22) was used to determine the effect of electrode placement on observed R and Xc and to evaluate the reproducibility of repeated R and Xc measurements. Significant differences were identified by Scheffé contrasts (23). Standard regression analysis (24) was used to relate R and Xc measures with standard indices of human body composition. Significant differences between correlation coefficients were determined by using the Z-transformation analysis (24).

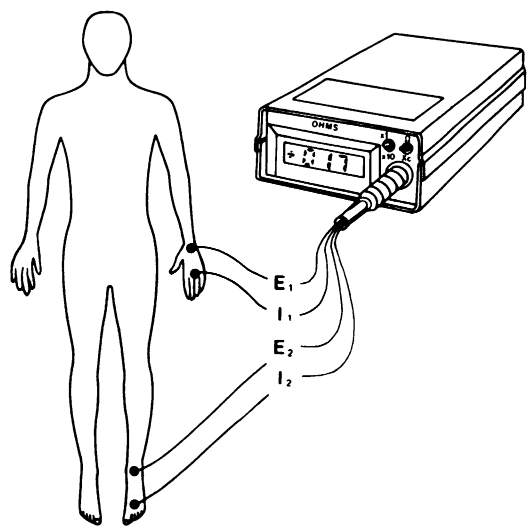

FIG 1. Diagrammatic representation of impedance plethysmograph using a four electrode arrangement. See text for details.

Results

Table 1 summarizes the physical characteristics of the subjects who had a wide range in FFM, TBW, and TBK.

Electrode placement influenced the observed R but not the Xc values (**Table 2**). Electrode configurations using the right arm had significantly lower ($p < 0.05$) R values than did the arrangements using the left arm. Among the four electrode configurations, the

TABLE 1
Physical characteristics of 37 male subjects

	Mean ± SD	Range limits
Age, yr	28.8 ± 7.1	19–42
Height, cm	180.7 ± 8.0	163.1–194.8
Mass, kg	86.9 ± 22.4	51.8–135.4
Body fat, %*	20.2 ± 7.6	7.8–43.0
Fat free mass, kg	68.4 ± 14.0	44.6–98.1
Total body water, L	50.6 ± 10.3	33.0–71.3
Total body potassium, g	167.5 ± 38.1	114.7–258.5

* Calculated from hydrodensitometry according to Brozek et al (1).

[5] 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.

TABLE 2
Effects of electrode placement on observed bioelectrical resistance (R) and reactance (Xc) in 37 men

Resistance (ohm)					
Rt^{*}_{arm}/Rt_{leg}	Rt_{arm}/Lt_{leg}	Lt_{arm}/Lt_{leg}	Lt_{arm}/Lt_{leg}	Low†	Mean‡
446.0[§][‖] ± 61.9	446.7[‖] ± 63.6	453.0[**] ± 68.4	453.6[**] ± 65.8	443.0[‖] ± 62.7	450.0[**] ± 64.6
Reactance (ohm)					
Rt_{arm}/Rt_{leg}	Rt_{arm}/Lt_{leg}	Lt_{arm}/Lt_{leg}	Lt_{arm}/Rt_{leg}	Low	Mean
59.8 ± 7.5	60.3 ± 7.9	60.5 ± 8.2	60.4 ± 8.0	60.1 ± 8.0	60.3 ± 7.8

* Rt = right, Lt = left.
† Lowest value of four electrode placements.
‡ Average value of four electrode placements.
§ Values are mean ± SD.
‖** Values in a row with different superscripts are significantly different ($p < 0.05$).

mean of the lowest R values for all subjects was similar to the average value observed using the right arm, but was significantly lower ($p < 0.05$) than the mean R of all four electrode configurations. Perhaps the similarity in R values is due to the fact that 32 of the 37 men had indicated that their right arm was dominant in physical activities. Based upon this observation and the results of Hoffer et al (13) who showed a strong inverse relationship between impedance and TBW, we have used the lowest observed R value as representative of an individual in further analyses.

The differences in R values observed with the various electrode placements probably reflect differences in conductor volume along the transmission pathway between one foot and one arm. However, the significance of these differences is negligible because the impedance plethysmograph introduces a constant current that provides a deep homogenous electrical field in the variable conductor of the body. Thus, any differences in the measured R values that reflect differences in the conductor volume in the transmission pathway are probably due to differences in muscle mass. Based upon the data presented in Table 2, the largest difference in R values observed across all electrode placements was 1.5%, and the mean variability in R values using all electrode configurations was less than 1%.

The stability of R measurements is shown in **Table 3.** In this group, the men were right handed and the lowest R values were recorded using the electrode configuration on the right side of the body. No significant difference ($p > 0.05$) was found among R values determined on five successive days. The individual coefficients of variation for these R values ranged from 0.9–3.4%, and the average precision was 2%. The test-retest correlation coefficient was 0.99 for a single measurement and the reliability coefficient for a single measurement over 5 days was 0.99.

A summary of correlation coefficients relating various indices and measurements of body composition is presented in **Table 4.** Significant ($p < 0.0001$) inverse relationships were found between R and FFM, TBW, and TBK. Similar relationships also were observed between Z and these measures. There was no significant difference in the magnitude of the correlation coefficients calculated using R and Z values.

Significantly lower ($p < 0.001$) correlation coefficients were observed between these body composition measures and Xc. Because the correlation coefficient relating R and Z values ($r = 0.99$) was significantly greater ($p < 0.001$) than that between Xc and Z ($r = 0.70$), subsequent regression analyses have used the R values (eg, resistive impedance).

These data support the hypothesis of Nyboer (25) that injection of a constant low level alternating electrical current at radio frequency into the body results in an impedance whose R is a good measure of ionic conductive volume whereas Xc is a measure of the dielectric or nonconductor space attributable to cell membranes.

TABLE 3
Reliability of bioelectrical resistance measurements (ohms) determined across Rt_{arm}/Rt_{leg} in 14 men on 5 successive days

Subject	Day 1	2	3	4	5	Mean ± SD	CV*
A	546	552	552	566	528	544 ± 16	2.9
B	460	456	455	448	463	459 ± 8	1.7
C	455	459	461	447	457	456 ± 5	1.1
D	489	500	507	494	485	498 ± 11	2.2
E	477	483	485	453	478	476 ± 12	2.5
F	530	544	541	533	521	534 ± 9	1.7
G	377	387	399	386	380	386 ± 8	2.1
H	518	530	520	507	509	514 ± 12	2.3
I	497	552	527	516	512	521 ± 18	3.4
J	508	529	516	522	513	515 ± 10	1.9
K	385	388	381	373	382	380 ± 8	2.1
L	432	430	426	426	420	428 ± 5	1.2
M	412	408	407	385	409	405 ± 10	2.4
N	526	539	528	529	533	531 ± 5	0.9
Mean	475	482	471	475	474		2.0
SD	±57	±60	±59	±60	±54		±0.7

* CV = (SD/mean) 100%.

Significant ($p < 0.01$) increases in the correlation coefficients were found when height^2/R, or height$^2 \times$ conductance since conductance = 1/R, was used as a predictor of FFM, TBW, and TBK. These relationships are presented in **Figure 2.**

Discussion

The results of the present study have demonstrated strong relationships between bioelectric impedance measurements and FFM, TBW, and TBK suggesting this method may be very useful as a tool for routine assessment of human body composition. The technique is safe and noninvasive; it requires no special skills on the part of the operator or the subject; subject cooperation is minimal; measurements are reliable and rapid; and the instrument is inexpensive and portable. These characteristics offer distinct advantages over existing methods of determining human body composition and make this technique uniquely suited for nutritional surveys and epidemiological studies.

TABLE 4
Correlation matrix of selected variables*

	Mass	FFM	FM	Density	TBK	TBW	M/Ht^2	R	Xc	Z
Height	0.63‡									
FFM	0.91§									
FM	0.85§	0.55‡								
% Fat	0.65‡	0.29	0.93§							
Density	−0.65‡	−0.29	−0.92§							
TBK	0.87§	0.97§	0.48	−0.22						
TBW	0.90§	0.96§	0.56‡	−0.31	0.96§					
M/Ht^2	0.94§	0.79§	0.89§	−0.75‡	0.71‡	0.80§				
R	−0.76§	−0.86§	−0.45	0.23	−0.79§	−0.86§	−0.77§			
Xc	−0.50†	−0.54‡	−0.31	0.16	−0.54‡	−0.55‡	−0.47†	0.71‡		
Z	−0.77§	−0.86§	−0.45†	0.22	−0.83§	−0.86§	−0.78§	0.99§	0.70‡	
Ht^2/R	0.86§	0.98§	0.49†	−0.22	0.96§	0.95§	0.73‡	−0.89§	−0.64‡	−0.89§

* n = 37.
† <0.01.
‡ p < 0.001.
§ p < 0.0001.

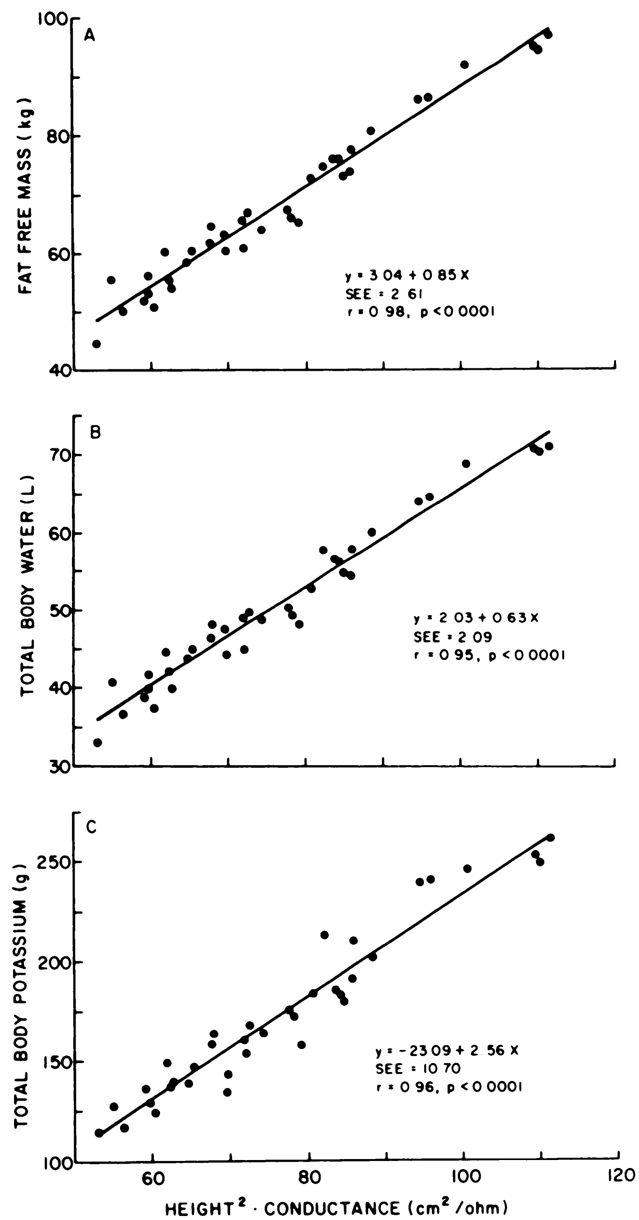

FIG 2. Linear regressions on conductance (1/Resistance) measurements corrected for height (13) of: A, fat-free mass; B, total body water; and C, total body potassium.

The high correlation coefficients calculated between conductance × height^2 (13) and various indices of human body composition indicate the validity of the impedance method. While any estimate of body composition is limited by errors in the experimental method and in theoretical assumptions, it is very encouraging to note that the experimental or technical error of the resistive impedance measurements was 2%, which is similar to, if not smaller than, that determined for the other methods used in this study.

All in vivo estimates of human body composition are indirect. Therefore, the accuracy of these estimates is questionable. One calculates FFM or percent body fat by relating primary measurements such as TBW, TBK, or D_b to "biological constants," derived from direct chemical analyses of laboratory animals and human cadavers, that assume the relatively constant composition of the fat-free body and body fat. The fat-free body is assumed to have a density of 1.1 g/cc at 37°C (1), a water content of 72–74% (2, 26), and a potassium content of 2.34–2.73 g/kg in men and 1.95–2.34 g/kg in women (27).

Using independent methods in the present study, we calculated the chemical composition of the FFM (eg, component/FFM). On the average, the potassium content of the fat-free body was 2.5 ± 0.12 g/kg (range: 2.4–2.78 g/kg) which is equivalent to the 2.46 g/kg reported by others who related TBK assayed by external counting of ^{40}K to FFM determined by densitometry (28). Our value is less than the commonly used value of 2.66 g/kg, obtained by direct chemical analysis of four cadavers (29), that has been shown to overestimate FM in civilian and military populations (30–32).

Our data indicate the FFM contains 74.1 ± 1.3% water (range: 71.1–75.1%) which agrees with the value of 73.5% reported by Loeppky et al (33) who measured TBW by tritium dilution and FFM by densitometry in 35 men. This calculated hydration of the FFM is similar to the direct dessication value of 73.2% observed in some mammals (2, 34).

The results of the present study have shown that bioelectrical impedance is a reliable and valid method of assessing human body composition and could prove invaluable in the field assessment of nutritional status. However, additional work is needed to determine the relationship between impedance components and direct chemical analyses of the components of the fat-free body in animals, and to establish the validity and the sensitivity of this method in patients with alterations in body water distributions and electrolyte composition and to changes in body composition associated with physical training and weight loss. Also, research is required to establish the validity of the impedance method in populations with abnormal body compositions such as cancer and renal patients.

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