Determination of Body Fluids by the Impedance Technique

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ALTHOUGH MOST INDIVIDUALS are concerned about body weight, weight is not the ideal parameter for determining nutritional status. Among the overweight, it is important to differentiate between those whose weight is increased because of greater muscle mass and those whose weight is increased because of excess body fat. Among the underweight, it is important to differentiate between those who have decreased body fat stores and those who have decreased intracellular mass, and more importantly to grade the degree of depletion for both of these components.

For the purposes of this discussion of body composition, the body can be viewed as the sum of two components, fat and fat-free mass. This two-compartment model of body composition was derived from animal studies, where fat is defined as all the lipid extractable mass (i.e., triglycerides and structural lipids) and fat-free mass is defined as all the remaining mass. Fat-free mass, which therefore includes water, protein, and minerals, can be further separated into intracellular and extracellular fat-free mass. The intracellular component includes the potassium-rich oxygen consuming organelles that are vital to sustaining life.

Current methods for determining the size of these various components of the body are either inexact, invasive, or dependent on expensive or slow instrumentation. Bioelectrical impedance, which is rapid, noninvasive, and relatively inexpensive has been suggested as an alternative method for measuring body composition. The potential for the impedance technique arises from the very different electrical properties of the above components of body composition.

THEORY OF BIOELECTRICAL IMPEDANCE ANALYSIS

The bioelectrical properties of an organism depend on the geometry of the organism and its specific resistivity. The latter varies as a function of the composition of the tissue(s) and the frequency of the test signal.

In 1969, Hoffer et al. [1] proposed that the complex geometries of the human body could be empirically treated as a single conductor of uniform cylindrical geometry. Assuming that the test signal frequency is constant, then the impedance (Z) is a function of the cross sectional area (A) and length (L) of the conductor (Figure 1a):

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

where ρ is the specific resistivity. Multiplying the right side of equation (1) by L/L and setting AL equal to the volume (V) of the conductor yields:

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

Rearranging equation 2 gives:

$$V=\rho L^2/Z.$$

Thus, the volume of the conductor can be related to the two readily measured parameters of length and impedance.

This volume can be interpreted with respect to body composition if the body is viewed as several components with differing resistivities that are arranged in parallel (Fig. 1b). Using this model, the volume estimated from length and impedance is closely approximated by that of the component with the lowest resistivity.

The resistivity of adipose tissue is considerably greater than that of muscle, and the difference is in proportion to the water content of these tissues (i.e., about 75 percent of weight for muscle and 5 to 20 percent for adipose [2]). From this difference it can be reasoned that fat, which is anhydrous, has a very high resistivity and that the volume derived from equation (3) is related to fat-free mass, or more specifically some compartment of the water in fat-free mass. This fat-free compartment depends on the frequency of the test signal. At frequencies between 100 Hz and 100 MHz, cell membranes have low electrical permitivity, and thus the impedance reflects the extracellular fluid [2]. At higher frequencies, the resistance of the cell membrane begin to short out because of the capacitance of the cell. At 300 MHz, there is virtually no difference between the resistivity of normal saline and lean tissue [2]. Thus, at these higher frequencies, the volume derived from equation (3) is related to total body water. The impedance, however, does depend on electrolyte concentration, hence the comparison against normal saline rather than water.

The dependence on electrolyte concentration would be a problem, except that the concentrations of electrolytes in body fluids are relatively constant in healthy subjects [3]. Moreover, the choice of frequency is less critical then would

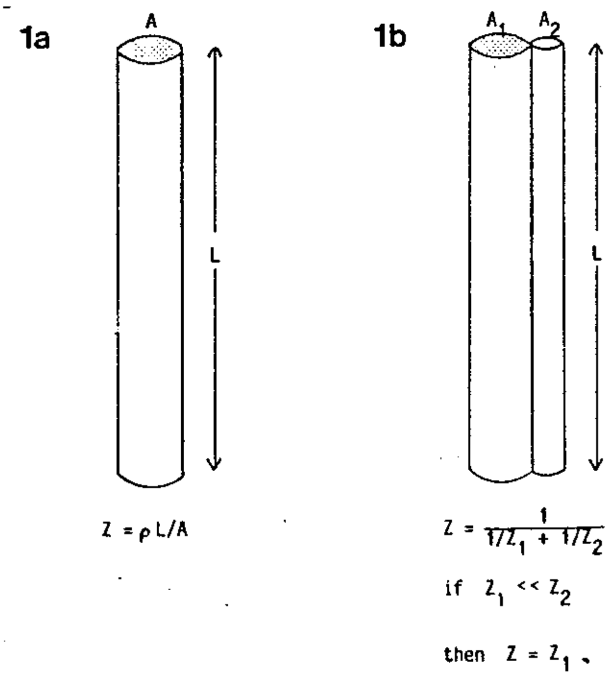

Figure 1.
(a) If the body is viewed as a single conductor with uniform geometry, then the impedance is a function of cross sectional area and length.
(b) If the body is viewed as two compartments of widely differing impedances, then the total impedance is nearly equal to the compartment with the lesser impedance.

be expected because the relationship between intracellular water and extracellular water is also relatively constant [4]. Thus, the empirical relationship between body water, length, and impedance would not be expected to display a very large intersubject variability in healthy subjects. Furthermore, the relationship between total body water (TBW) and fat-free mass (FFM) is quite constant [5]. Thus, most recent investigations have compared either TBW or FFM against impedance using impedance analyzers employing signal frequencies of 50 to 100 KHz.

HUMAN APPLICATIONS

For purposes of calculating bioimpedance, conductor length is taken as the stature (cm) of the individual. The resistance and reactance (Xc) of the whole body (transmission pathway) is determined by detecting the voltage drop between current-introducing electrodes (*I*, distal) and adjacent dectector electrodes (*E*, proximal) placed at the hand-wrist and foot-ankle locations (Fig. 2). All published studies have used this tetrapolar method, employing aluminum foil-spot electrodes and conductivity gel. Lukaski et al. [6] found that left or right electrode placement influenced the observed resistance (R), but not the reactance values. However, the largest difference in R values was only 1.5 percent and not significant. By standard convention, most investigators have used a right sided ipsilateral configuration. Bioimpedance analysis is generally performed with subjects lying supine, with extremities away from the trunk, and after an overnight fast or at least two hours postprandial. Reliability of within-day and week-to-week impedance measurements has been excellent, with correlation coefficients of 0.99 [6]. As long as intake and strenuous physical exercise are not performed during this two-hour period, the interval between the last meal or drink and the measurement, habitual levels of physical activity, or menses have little influence on the

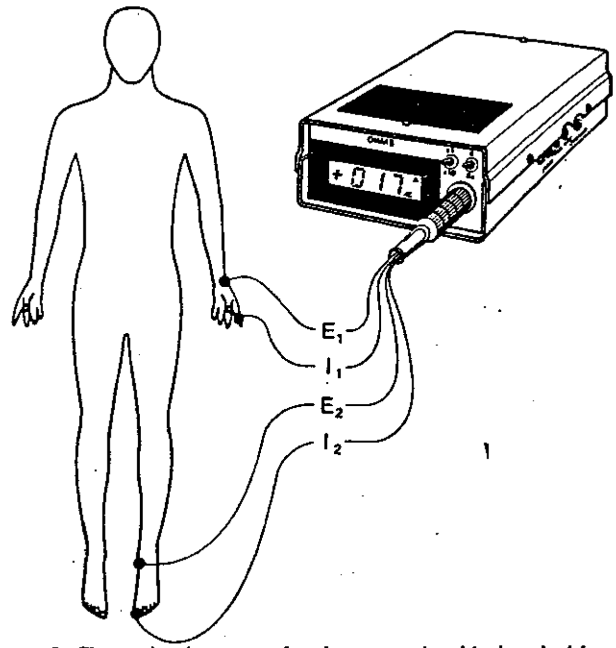

Figure 2. Electrode placement for the tetrapolar, bioelectrical impedance analysis of body fluids and body composition.

TABLE 1
Validation Studies of Bioelectrical Impedance Analysis

Total Body Water and Fat-Free Mass

Study	*n (M/F)*[a]	*Age (Yrs)*	*Validation Method*[b]	*Predictive Variables*[c]	r^2[d]	*SEE*[d]
Lukaski et al. [8]	114 (47/67)	19-50	dFFM	S^2/R, BM, Xc	0.984	2.06
Kushner and Schoeller [9]	40 (20/20)	19-65	D_2O-TBW	S^2/R, BM, Gender	0.980	1.37
Segal et al. [10]	75 (34/41)	17-59	dFFM	S^2/R, BM, Gender	0.925	3.06
Hughes et al. [11]	66 (30/36)	49-74	dFFM	S^2/R, BM, Xc	0.945	2.65
Van Loan et al. [12]	188 (123/65)	18-64	dFFM	S^2, BM, R, Gender, Age	0.917	3.23
Van Loan et al. [12]	174 (NS)	18-64	D_2O-TBW	S^R, BM, R, Gender, Age	0.871	2.92
Lukaski et al. [13]	151 (NS)	19-50	dFFM	S^2/R, Xc, BM, Gender	0.983	2.10
Segal et al. [14]	1567 (1069/498)	17-62	dFFM	S^2, R, BM, Age, % BF	M 0.902 0.884 F 0.829 0.902	2.47[e] 3.03 1.97 1.97
Hoffer	34		D_2O	S^2/R	0.92	3.99

[a]Number of subjects (*n*) with breakdown according to gender.
[b]dFFM = densitometry derived FFM, D_2O-TBW = deuterium dilution space.
[c]S^2/R = stature²/resistance, BM = body mass, X_c = reactance, R = resistance, %BF = percent body fat, NS = not stated.
[d]r^2 = Pearson's correlation coefficient, SEE = standard error of estimate.
[e]First equation for lean men (M) or women (F); 2nd equation for obese, men and women, respectively.

impedance measurement [7].

All published validation studies of bioimpedance analysis have used a bioimpedance analyzer that delivers a 800 uA current at 50 KHz. As stated, this frequency penetrates the extracellular fluid, but is suitable for measurement of body composition assuming a two-compartment model (i.e., FFM and FM). Thus, comparisons have been made between bioimpedance analysis and TBW (by isotope dilution), fat-free mass measured by hydro-densitometry (dFFM), and total body potassium (TBK). Using single-factor regression analysis, Lukaski et al. [6] observed highly significant coefficients between stature^2/R (S^2/R) and fat-free mass ($r = 0.98$), total body water ($r = 0.95$), and total body potassium ($r = 0.96$) in 37 healthy young men. Thus, the relationship proposed by Hoffer et al. [1] between whole body impedance and lean hydrated tissue was confirmed.

A summary of the published validation studies between bioimpedance analysis and TBW or FFM is presented in Table 1. Both males and females are represented, ranging in age from 17 to 74 years and with varying body fat from 3.8 percent to 54.9 percent. The racial background of those subjects is generally not indicated. A stepwise multiple regression analysis was carried out in each study to identify the best predictors of TBW or FFM. Finally, the total variability accounted for by the equations (r^2) and the computed standard error of estimate (SEE) are shown in the last columns.

In five of these studies, the variable S^2/R was the single best predictor of TBW or FFM, and accounted for 88 to 97.8 percent of the total variability. The addition of body mass to the predictive equations was consistently found to reduce significantly the SEE in all studies. Two other variables, reactance or gender, were also significant in all studies. Overall, these multiple variable equations accounted for 83 to 98.4 percent of the of the total variability associated with TBW or FFM.

The mean standard error of the estimate obtained from these equations is 2.1 liters total body water or 2.5 kg fat-free mass. Although the bioimpedance technique appears useful in estimating lean tissue in the healthy-lean or obese adult, its application in children, individuals with an abnormal hydration state, or in assessing weight change has not been thoroughly investigated.

By measuring reactance and employing both a low- and high-frequency current, bioimpedance has an even greater potential of measuring body composition. As indicated above, this technique would give measures of extracellular water and total body water which lend themselves to a three-compartment model (i.e., intracellular mass, extracellular mass, and fat mass). This model would be particularly useful in the assessment of body composition in the emaciated patient and those undergoing nutritional restitution, where an abnormal extracellular mass/intracellular mass ratio is found. Preliminary studies from McDougal et al. [15] and Segal et al. [16] support the utility of bioimpedance under these conditions.

CONCLUSIONS

Bioimpedance analysis is a rapid, portable, reliable and simple-to-operate method that improves the accuracy of predicting total body water and fat-free mass compared to other traditional anthropometric techniques. Although there is a general uniformity regarding the predictive variables generated by the multiple regression equations, the individual coefficients differ since they are population specific. There is an increased need to pool subject data so as to develop a generally accepted equation(s) with wide applicability. In addition, validation studies must be conducted in subjects with nutritional disorders that affect body water. These studies should also include measurement of the intracellular and extracellular water compartments.

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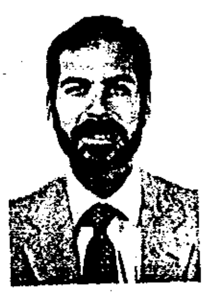

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