Bioelectrical Impedance Analysis

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The study of the electrical properties of biological systems has been of interest since the discovery of electricity by Galvani. The fundamental electrical properties of tissues were studied initially using tissue and cell suspensions. With the development of newer technology, the study of the bioelectrical properties of living systems advanced from studies of isolated cells and tissues to investigations of the whole body. This evolution led to the application of bioelectrical impedance analysis (BIA) to the study of body composition.

GENERAL MODEL OF BIOELECTRICAL IMPEDANCE ANALYSIS

This method is based upon the conductance of an applied electrical current in the organism. Application of a constant, low level, alternating current (AC) results in a frequency-dependent impedance to the spread of the current. Highly conductive fat free tissues contain large amounts of water and electrolytes and represent a low impedance electrical pathway, while cell membranes behave as electrical capacitors [1]. In general, at low frequencies (~1 kHz), the current passes through the extracellular fluids, while at higher frequencies (>50 kHz) it penetrates all water compartments [2].

The hypothesis that BIA can be related to conductive tissue mass 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 assuming a relatively constant conductor configuration, the bioelectrical impedance to the flow of current can be related to the volume of the conductor [3, 4]: Z = ρL/V where Z is impedance in ohms, ρ is volume-resistivity in ohm-cm, L is conductor length in cm, and V is volume in liters.

Although there are difficulties in applying this general equation to a system with such complex geometry and bioelectrical characteristics as the human body, this empirical relationship has been used to develop models relating bioelectrical impedance measurements to body composition.

Thomasset and his colleagues [5–7] first used bioelectrical impedance measurements to assess human body composition. Two stainless steel needles were inserted subcutaneously on the dorsal surfaces of one hand and the opposite foot. Whole body impedance was measured using 10 µA, AC, introduced at 1 kHz and at 100 kHz. At the low frequency, impedance was a linear function (n = 65, r = 0.71) of height²/extracellular fluid volume (Ht²/ECF), and at the high frequency, the impedance was a linear function (n = 44, r = 0.93) of height²/total body water (Ht²/TBW).

Using these impedance data, Jenin et al. [8] developed a relationship to predict the relative proportions of body water volumes (e.g., TBW/ECF) using the ratio of high frequency to low frequency impedance. In healthy subjects this ratio is relatively constant (1.3 ± 0.3, mean ± SD), while in pathological cases the ratio is much less than 1.3. Interestingly, this ratio declines with age and malnutrition, suggesting a loss of fat free tissue mass.

Although the work of Thomasset and his colleagues pioneered the application of impedance measurements to assess body water compartments, their approach had some disadvantages. The use of needle electrodes causes both subject discomfort and electrochemical reactions that alter the observed impedance values. These limitations restricted the acceptance of the Thomasset method and led to the use of four-electrode systems.

Hoffer et al. [9] used four surface electrodes placed on the dorsal surfaces of the right hand and left foot and introduced 100 µA, AC, at 100 kHz in 20 normal volunteers and 34 patients in whom TBW was estimated by tritium dilution. In both groups, the best predictor of body water was Ht²/Z (r = 0.92 and 0.93), which was similar to the general model for applying impedance measures to predict body composition.

They also examined the influence of varying signal frequency on the observed impedance values [10]. No change in impedance was found over a large range of frequencies (0.1–100 kHz), indicating that all body water compartments were penetrated over this frequency range. This observation has not been confirmed.

UPDATED APPLICATION OF BIOELECTRICAL IMPEDANCE ANALYSIS

Since these original applications, more sophisticated model development has occurred. A living organism con-
sists of cells and fluids arranged in a heterogenous pattern. In terms of electrical circuitry, cells and membranes exhibit series and parallel configurations. In a series pathway, the impedance to the flow of current is represented mathematically as the sum of the squares of resistance (R) and reactance (Xc). In a parallel pathway, the resistors and capacitors are quantitated as the sum of the reciprocal of individual R and Xc. Because the body is a mixture of resistors and capacitors arranged in both series and parallel orientations, the measurement of both R and Xc may be necessary in extending BIA in biological applications.

The importance of determining Xc is emphasized in the data of Nyboer and Sedensky [11], who obtained impedance measurements on nine female and 15 male patients before and after kidney dialysis. The largest change was found in mean Xc (50%; 52 to 75 and 43 to 68 ohms); smaller changes were found in average R (14%; 461 to 518 ohms) and in mean Z (12%; 464 to 523 and 552 to 640 ohms).

Resistive and reactive components of whole body impedance can be quantitated using modern impedance plethysmography and four surface electrodes. This technique, which introduces 800 μA, AC, at 50 kHz, permits investigators to develop and validate models of predicting human body composition.

Initial efforts focused on determining the relationship between impedance components and body composition variables in a relatively homogenous sample of men [4]. Significant relationships were found among impedance components and TBW, total body potassium (TBK), and fat free mass (FFM). Resistance was more strongly correlated with these variables than was Xc \( r = -0.86, -0.79, \) and \(-0.86\) vs. \(-0.55, -0.54, \) and \(-0.54, \) respectively. However, the strongest correlations were found with \( Ht^2/R, \) or conductance \( (r = 0.95, 0.96, \) and \( 0.98).\)

To determine the error of predicting FFM and estimating relative body fatness, a sample of 151 females and males aged 18–50 yr underwent determinations of R and Xc using BIA and body composition by densitometry [12]. A stepwise multiple regression model for estimating FFM using impedance components was developed: FFM [kg] = 0.734Ht²/R + 0.116Wt + 0.096Xc – 0.878G – 4.03 \( (R^2 = 0.984, \) see = 2.06), in which G or gender is dummy coded 1 = male and 0 = female, R is the lowest resistance value observed among the four electrode placements, Xc is determined across the right wrist to ankle axis and Wt is body weight. This model was cross-validated in an independent sample of 161 females and males aged 18–73 yr [13]. The relationships between densitometrically determined body composition variables and those predicted using bioelectrical impedance analysis are shown in Figs. 1 and 2. The slopes of these lines are not different than 1, and the intercepts are similar to 0 [13].

To determine the effect of body fatness on the error of predicting FFM using BIA, the residual scores (calculated as the difference between FFM determined by densitometry and predicted by BIA) were regressed against percent body fat (23 ± 10%) and body fat mass (18 ± 10 kg). Weak correlation coefficients were found \( (r = 0.31 \) and \( 0.34). \) The coefficients of determination indicate that only 10–12% of the variability in the residual scores can be attributed to body fatness. Thus, body fatness does not appear to significantly bias impedance predictions of densitometrically determined FFM.

The variability in repeated R measurements made under
controlled conditions over 5 days indicates a 2% mean coefficient of variation [14]. This small intra-individual variability probably reflects small daily alterations in body water compartments.

In a preliminary trial, we determined TBW by deuterium dilution [15] and ECF from the corrected bromide space [16] in 25 females and 25 males aged 18–55 yr. Stepwise multiple regression models were determined, TBW [L] = 0.410Ht³/R + 0.137Wt − 0.071A + 2.81G + 4.41 [R² = 0.96, see = 2.11], and ECF [L] = 0.087Ht²/R + 0.001Wt + 0.017Xc − 0.009A − 0.017 [R² = 0.90, see = 1.0]. Gender, R, and Xc are used as described above; A is age.

In our models, specific R and Xc values have been identified. This indicates that selection of proper electrode placement is important. Figure 3 shows the frequency distribution of the source of low R values in a sample of 500 subjects and indicates that about 45% of the low R values were found along the transmission axis of right wrist-ankle. Thus, if R is arbitrarily measured using electrode placement along this axis, error could be expected in determining the low R value in more than 50% of the subjects. We also investigated the use of reported hand dominance on the prediction of transmission axis with the low R value and found this approach accurate in only 40% of the subjects. These findings establish the need to measure impedance using the four longitudinal transmission axes of the body to assure the appropriate R and Xc values for valid use of our models.

Kushner and Schoeller derived an impedance model to predict body water in humans [17]. Their group equation including gender is similar to our prediction model. Use of their equation in a group of 18 prospective patients showed good agreement with measured water values and mean errors of 0.6–1.0 l.

**TABLE 1**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Resistance</th>
<th>Reactance</th>
<th>Fat free mass</th>
<th>Body fat</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>ohms</td>
<td>kg</td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>Control</td>
<td>410 ± 12</td>
<td>55 ± 2</td>
<td>69.8 ± 2</td>
<td>16.5 ± 0.5</td>
</tr>
<tr>
<td>Electrode</td>
<td>510 ± 15</td>
<td>62 ± 2</td>
<td>59.1 ± 1</td>
<td>29.2 ± 0.6</td>
</tr>
<tr>
<td>Placement</td>
<td>480 ± 16</td>
<td>60 ± 1</td>
<td>61.7 ± 2</td>
<td>25.2 ± 0.6</td>
</tr>
<tr>
<td>Dehydration</td>
<td>370 ± 11</td>
<td>58 ± 1</td>
<td>76.2 ± 1</td>
<td>8.1 ± 0.2</td>
</tr>
<tr>
<td>Exercise</td>
<td>300 ± 10</td>
<td>54 ± 1</td>
<td>90.9 ± 3</td>
<td>—</td>
</tr>
<tr>
<td>Conductive</td>
<td>395 ± 12</td>
<td>49 ± 2</td>
<td>71.4 ± 2</td>
<td>14.5 ± 0.4</td>
</tr>
<tr>
<td>surface</td>
<td>425 ± 14</td>
<td>59 ± 2</td>
<td>68.1 ± 2</td>
<td>18.5 ± 0.5</td>
</tr>
<tr>
<td>Warm skin</td>
<td>395 ± 12</td>
<td>49 ± 2</td>
<td>71.4 ± 2</td>
<td>14.5 ± 0.4</td>
</tr>
<tr>
<td>Cool skin</td>
<td>425 ± 14</td>
<td>59 ± 2</td>
<td>68.1 ± 2</td>
<td>18.5 ± 0.5</td>
</tr>
</tbody>
</table>

*Based upon model of Lukaski and Bolonchuk [13].

*Values in the same column with superscripts are significantly different than the control value (*, P < 0.05; **, P < 0.005).

*Mean ± SEM.

**TABLE 2**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Equation</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>LBM</td>
<td>16.4 ± 0.61 Ht²/R</td>
<td>0.88</td>
</tr>
<tr>
<td>ECM/BCM</td>
<td>2.4 ± 34.8/Xc − 5.97 × 10⁻⁵ [Ht⁻¹]</td>
<td>0.79</td>
</tr>
</tbody>
</table>

*McDougall and Shizgal [19].
Some physical factors, as shown in Table 1, can influence the validity of the impedance method to predict body composition. Improper electrode placement, voluntary dehydration, and depressed skin temperature (a 2°C drop) elevate R values and cause an underestimate of FFM. Conversely, use of a conductive surface (e.g., a metal examination table), elevated skin temperature (a 5°C increase), and brief, intense exercise depress the R values and result in overestimation of FFM values. Thus, controlling measurement conditions is necessary to obtain valid impedance predictions of body composition.

Routine assessment of body composition in critically ill, malnourished hospital patients is difficult and impractical. Traditional methods are not applicable because assumptions of relative constancy of chemical composition of the fat free body are not valid. Use of a multi-compartmental model of body composition is required. Neutron activation analysis may be indicated, but it is not generally available. Perhaps some of the new radiological techniques will be useful. Another available approach is the three compartment model of Moore et al. [18] that includes body cell mass, extracellular mass, and fat.

MacDougall and Shizgal [19] applied this approach to develop a preliminary model for body composition assessment in patients using bioelectrical impedance measurements. Sixty-four patients were studied, 41 were malnourished and 23 were considered normally nourished. The preliminary models (Table 2), containing the combined data of both groups, indicate a good relationship between lean body mass and $Ht^2/R$. The inverse of Xc was a good predictor of the ratio of extracellular to body cell mass. This suggests an important role of Xc in estimating the extracellular to intracellular masses and their fluid volumes.

CONCLUSIONS

The method of BIA is a safe, noninvasive technique that is rapid and convenient, and provides reliable and reasonable accurate estimates of body composition outside of the laboratory. It is a method that may be useful in many diverse applications.

LITERATURE CITED