Bioelectrical Impedance Analysis: A Review of Principles and Applications

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Whole-body bioelectrical impedance analysis (BIA) is widely used by researchers and clinicians as a noninvasive and safe method to estimate body composition and body water volume in children and adults. Development of new approaches, such as segmental and multifrequency analyzers, should greatly expand the utility of this electrical technique. This article reviews the principles, underlying assumptions, clinical applications and future directions of the BIA method.

Abbreviations: A = cross-sectional area, BIA = bioelectrical impedance analysis, D$_2$O = deuterium oxide, dFFM = densitometry-determined fat-free mass, E = applied voltage drop, ECW = extracellular water, FM = fat mass, FFM = fat-free mass, H = height, I = current, ICW = intracellular water, L = conductor length, R = resistance, SEE = standard error of the estimate, TBW = total body water, V = volume, W = weight, Xc = capacitance, Z = impedance, $\phi$ = phase angle, $\rho$ = specific resistivity

INTRODUCTION

Measurement of body composition has become an important procedure in nutrition assessment. A variety of techniques have been developed which can accurately measure the two major compartments of the body, the fat-free mass (FFM) and fat mass (FM). Whereas in vivo neutron activation and isotope dilution techniques primarily measure FFM, hydrostatic weighing estimates percent FM based upon the density of the two compartments. Although these methods are considered gold standards, they are expensive, require expertise, and demand substantial subject cooperation. Subsequently, various anthropometric techniques have been developed which are more appropriate to epidemiological, clinical, or hospital settings. However, the accuracy of these estimates is limited by inter- and intra-examiner error, changes in subcutaneous and internal fat distribution between males and females of different ages, and difficulty measuring ill patients.

Over the past decade, a technique has been developed which measures FFM based on the electrical properties of biological tissues. Bioelectrical impedance analysis (BIA) has many advantages over other methods in that it is safe, inexpensive, portable, rapid, easy to perform, and requires minimal operator training. The technique has become widely used in hospitals, health and fitness centers, and in field studies. For BIA to be used appropriately, however, the user should have a firm knowledge regarding the technique and its use. Therefore, this article will review the basic principles of electrical impedance plethysmography and its application to the measurement of human body compartments.

PHYSICAL PRINCIPLES

Impedance plethysmography refers to the measurement of variations in the amount of blood passing through an organ or limb by recording changes in electrical impedance across the body segment. The impedance technique is familiar to clinicians for the measurement of cardiac ventricular volume changes (impedance cardiography) and for the detection of venostasis resulting from iliofemoral thrombophlebitis. The application of BIA for measurement of total body water (TBW) by whole-body impedance

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has recently become widespread after being first described by Thomasset [1] and Hoffer [2] over 30 years ago.

The underlying principle of BIA is that the impedance of a geometrical isotropic conductor is related to its length and configuration, its cross-sectional area, and applied signal frequency (Fig. 1):

\[ Z = \frac{\rho L}{A} \]

where \( Z \) = impedance (ohm)
\[ \rho = \text{specific resistivity (ohm-cm)} \]
\[ L = \text{conductor length (cm)} \]
\[ A = \text{cross-sectional area (cm}^2) \]

Since any fraction remains unchanged if multiplied by a value which equals one, the above relationship may be multiplied by \( L/L \) which gives:

\[ Z = \frac{\rho L}{A} \times \frac{L}{L} \]

Since \( A \times L \) is equal to volume (\( V, \text{cm}^3 \)), the equation can be rearranged to solve for \( V \), such that:

\[ V = \frac{\rho L^2}{Z} \]

Therefore, by using a fixed signal frequency and measuring the length and impedance of the conductor, one can solve for the unknown variable, or volume.

Measuring the "electrical volume" of a body compartment, such as the TBW or FFM, is based upon the principle that various biological tissues act as conductors, semiconductors, or dielectrics (insulators). Electrical conduction in the body is ionic in type and related to the free ion content of the various salts, bases, and acids, their concentration, mobilities, and conducting medium temperature [2]. Whereas lean tissue contains large amounts of water and electrolytes and is highly conductive, fat and bone are dielectric substances and are poor conductors. Since an electrical current will follow the path of least resistance, compartments of the FFM, such as extracellular fluid and muscle, will dominate in determining the resultant total body impedance.

Electrical impedance and resistance are often used interchangeably in the BIA literature. In fact, impedance is a function of resistance (\( R \)) and capacitance (\( X_c \)) of the conducting substance, such that:

\[ Z^2 = R^2 + X_c^2 \]

Whereas \( R \) is equal to the pure opposition to flow of an alternating current, \( X_c \) is the opposition to flow of electric current caused by capacitance produced by tissue interfaces and cell membranes. By definition, a capacitor consists of two or more conducting plates separated from one another by an insulating, nonconductive material used to store charge. In the body, cell membranes theoretically act as capacitors with a bilayer of polar proteins and phospholipids separated by a core of nonconductive lipid.

Total body impedance is a combination of resistance and reactance across biological tissues.

As stated in equation 1, impedance is a function of the L and A at a given fixed frequency. This is because the values of the two properties, R and Xc, are dependent on the signal frequency of the alternating current. As seen in Figure 2, at high radio frequencies biological systems become purely resistive and the reactive component of impedance approaches zero. This implies that a uniform distribution of current is produced which effectively short
circuits the capacitive cell membrane. At lower frequencies, Xc begins to increase in proportion to R [3].

The relationship between Xc and R of a circuit can be expressed by the arc tangent, or phase angle (φ), where Xc is plotted along the ordinate axis, R plotted on the abscissa axis, and the resultant Z is defined by the tangent line. Thus, electrical circuits of pure resistance (high signal frequency) have a φ of 0° and circuits of pure reactance (cell membranes with no fluid) have a φ of 90°. At frequencies commonly used for assessing physiological activity, the reactive component of bioelectrical impedance (Xc) is very small. The average φ for healthy individuals is thought to be <15°, indicating primarily a resistive (R) biological system [3]. By using phase sensitive electronics, impedance plethysmographs or analyzers can separate the Xc and R components of the conductor substance.

As stated previously, the underlying paradigm of BIA assumes that the body is an isotropic conductor with a uniform length and cross-sectional area. This assumption is not entirely correct. First, the geometrical shape of the human body more closely approximates a series of five cylinders (two arms, two legs and a trunk) excluding the head (Fig. 3). Since R is inversely proportional to the cross-sectional area, the upper and lower extremities (which have the smallest cross-sectional area) will have the most influence on whole-body R measurements. Conversely, the trunk, which contains approximately 50% of the body mass, will contribute <5–12% of total body R [5].

Secondly, isotropic conduction infers that current density is uniformly distributed along axes in all directions. This does not occur throughout the human body. Due to inclusion of dielectric conductors within the body, such as the lungs or intramuscular fat, conduction is anisotropic or heterogeneous through certain body segments [5].

Thirdly, ρ of equation 1, which describes the amount of resistance to the flow of current per unit length of a specific conductor, has generally been neglected in BIA body composition studies. However, in biological conductors ρ is not a physical constant and will vary depending upon the tissue microstructure, hydration status, and concentration of electrolytic ions [6,7]. Unfortunately, the values for tissue resistivities are not well established and are difficult to measure. Chumlea et al [8] estimated segmental specific resistivities in a group of adults and children by reformulating equation 3. Mean segment ρ of the arm and leg were larger in adult females and males compared to children by 22 and 16%, respectively. Furthermore, the mean ρ of the trunk was approximately two to three times greater than the individual segments. Fuller and Elia [9] also demonstrated that segmental specific resistivities of obese subjects were considerably greater than those of normal weight subjects. Despite all of these limitations, however, impedance plethysmography has been
found to be a useful technique in body composition measurement.

**MEASUREMENT OF BIA**

Whole-body impedance or resistance is measured by employing Ohm's law, which states that the R of a substance is proportional to the voltage drop of an applied current as it passes through the resistive substance:

\[ R = \frac{E}{I} \text{ where } E = \text{applied voltage drop (volts)} \]
\[ I = \text{current (amperes)} \]

A right-sided tetrapolar surface electrode technique has been adopted by essentially all investigators since the landmark study of Hoffer [2]. As displayed in Figure 4, two distal current or signal introducing electrodes (I) are placed on the dorsal surfaces of the hand and foot proximal to the metacarpal-phalangeal and metatarsal-phalangeal joints, respectively. The two voltage sensing electrodes (E) are applied at the pisiform prominence of the wrist and between the medial and lateral maleolii of the ankle. Two of the most frequently used analyzers are the RJL model BIA-101 and Valhalla model 1990B. The RJL impedance analyzer (RJL Systems, Detroit, MI) delivers an imperceptible constant 800 μA alternating current at a fixed 50 KHz frequency via the distal I electrodes and detects the voltage drop via the proximal E electrodes. The Valhalla instrument (Valhalla Scientific, San Diego, CA) introduces a 500 μA alternating current at the same frequency of 50 KHz. The measured R and Xc are immediately displayed by the analyzer.

Standard measurement conditions that have been adopted by researchers include having the subject lie supine with limbs abducted, cleaning the electrode placement skin surface with an alcohol swab, and repeating the R and Xc measurements in duplicate or triplicate (Table 1). In studying the effect of electrode configuration on R and Xc, Lukaski et al [10] found that an ipsilateral (right arm/right leg or left arm/left leg) and contralateral (right arm/left leg or left arm/right leg) placement of electrodes produced a mean difference in R of <1.7%. Among the four electrode configurations, the lowest whole-body R values were seen using the right ipsilateral positions. A lower right-sided R measurement was also observed by Graves et al [11] in a study of 146 subjects. Lukaski [12] has subsequently recommended that the impedance measurements be made using all four transmission axes to obtain the lowest R and Xc values for the individual. However, from a practical view, right-sided measurements alone are most often obtained.

Violation of the conditions listed in Table 1 may cause measurement error. Elson et al [13] found that a 1 cm displacement of sensor electrodes from the anatomical

Fig. 4. Electrode placement for whole-body right-sided tetrapolar bioelectrical impedance analysis, where I is a current-introducing electrode and E is a voltage-sensing electrode.

reference points resulted in a 2% error in R. The ambient room temperature, via the effects on cutaneous blood flow or compartmental changes in water, may also alter measured R. Caton et al [14] detected an average 8% increase in R when the room was cooled from 35 to 14.4°C. Other physiologic causes for cutaneous vasconstriction, such as hypotension or severe congestive heart failure, have not yet been evaluated. BIA measurements taken immediately following a meal or beverage, after strenuous exercise, or during the menstrual cycle have resulted in varying changes in R, ranging from 0.8 to 3.3% [15–17].

The reliability or reproducibility of repeated impedance measurements has been tested by several investigators [10,13,16,18]. The mean coefficient of variation for within-day individual R measurements has ranged from 0.3

<table>
<thead>
<tr>
<th>Table 1. Suggested Measurement Conditions for the Tetrapolar Whole-Body Bioelectrical Impedance Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lie in supine position on nonconducting surface</td>
</tr>
<tr>
<td>Limbs abducted at approximately 45°</td>
</tr>
<tr>
<td>Preparation of skin surfaces with isopropyl alcohol</td>
</tr>
<tr>
<td>Accurate placement of electrodes at anatomical sites (see text)</td>
</tr>
<tr>
<td>Normal room temperature</td>
</tr>
<tr>
<td>Fasted state (at least 2 hours postprandial)</td>
</tr>
<tr>
<td>No previous strenuous exercise, alcohol or dehydration (at least 12 hours)</td>
</tr>
</tbody>
</table>

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to 2.8%. Daily or weekly intraindividual variability has ranged from 0.9 to 3.6%. In addition to biological factors, another potential source of variation is the analytical accuracy and precision of the impedance analyzer. The accuracy of the RJL analyzer to measure R, using external electronic resistors from 100–750 ohms, was found to be within 5 ohms of the expected values [19,20]. However, differences in readings of 7–16 ohms were seen when measuring subjects with three separate instruments [21]. Similarly, Graves et al [11] observed deviations of up to 36 ohms when four different impedance analyzers were compared on 146 healthy subjects.

APPLICATIONS

Measurement of Body Composition in Weight-Stable Subjects

Based on the original work of Thomasset [1], Hoffer et al [2] confirmed the empirical relationship generated in equation 3 when they measured TBW in 20 normal volunteer subjects. Using the tetrapolar impedance technique and applying a 100 µA current at a frequency of 100 KHz, the best predictor of TBW was H²/Z, which accounted for 84% of the total variability (R²). Height (cm) was used as a measure of L instead of the actual pathway length since it was more easily obtained. Lukaski et al [10] also found that the predictor H²/R yielded the highest correlation coefficients when regressed against TBW (r = 0.95), total body potassium (r = 0.96) and densitometry-determined FFM (dFFM) (r = 0.98). Since these two initial studies, many investigators have validated the use of BIA for the estimation of TBW, measured by isotope dilution (D₂O-TBW or H₂O-TBW) or dFFM.

Summaries of validation studies comparing BIA with TBW or FFM in adults and children are presented in Tables 2 and 3. These studies were all conducted using the RJL analyzer. The adult studies represent a broad range of males and females, aged 17–83 years, with body fat varying from 3 to 59%. Multivariate regression analysis was carried out in each study to identify the best predictors of TBW or FFM. In general, excellent empirical relationships were found between TBW or FFM and BIA. In eight of the 12 adults studies, the impedance index H²/R was the best single predictor of these body compartments, accounting for 59–98% of the total variability. The accuracy of predicting TBW or FFM statistically improved by the inclusion of weight in all equations and age and gender in most. Similar correlations between H²/R and TBW or FFM were seen in the eight pediatric studies shown in Table 3. A comparison of selected equations for the prediction of TBW or FFM from the impedance index, H²/R, is seen in Table 4. Despite the broad range of ages and body compartment sizes, the regression equations are remarkably similar with highly significant correlation coefficients.

The observation that additional independent variables, e.g., weight, age and gender, improve the accuracy of the equations reinforces the underlying conceptual problems in applying impedance principles to whole-body measurements. It has already been noted that the body is not a homogeneous conductor with uniform cross-sectional area, and that the p of tissues are not constant. The addition of these factors most likely adjusts for the geometrical complexity of the human body and other anthropometric differences between individuals, especially those reflecting trunk size.

Overall, the standard error of the estimate (SEE) obtained from the multiple regression equations in Table 2 range from 1.4 to 3.5 kg TBW and 2.0 to 3.6 kg FFM. When applying these measurement ranges to a standard 70 kg man with 60% body water and 18% body fat, this corresponds to an error in predicting TBW and FFM of 3–8% and 3.5–6%, respectively. Selecting a regression equation that is population or gender specific may be expected to improve the accuracy and precision of measurement but at the expense of less generalizability. In summary, the user should be familiar with the equation supplied by the manufacturer of the impedance analyzer, know which "gold standard" body composition technique was used to generate the equation, and ensure that standardized measurement conditions are observed (Table 1).

As seen in Table 2, some investigators found that height (or height²) and weight were better predictors of TBW or FFM than the impedance indices. For example, Diaz et al [25] found that after weight and height were entered into the multivariate equation, H²/R contributed <5% to the prediction of FFM. Jackson et al [36] used multiple regression to quantify the relative importance of bioimpedance measurements compared to standard anthropometric methods. The authors found that the anthropometric variables of height, weight or the sum of multiple skinfold measurements were more powerful predictors of FFM than the BIA parameter. Similarly, Helenius et al [37] observed that H²/R did not contribute to the estimation of percent body fat in overweight middle-aged men and women when added to selected anthropometric variables. Guo et al [38] found that H²/R improved the prediction of percent body fat for women, but not for men.

Thus, it has been argued by some investigators that height and weight account for the majority of the BIA prediction of FFM or TBW [39]. It is well established that there is a significant relationship between these compartments and an individual's height and weight. Based on body composition values from normal subjects, several regression equations have been previously developed for the prediction of the lean body compartments from height.
and weight alone with correlation coefficients ranging from 0.61 to 0.96 [40,41]. However, the accuracy of these formulas diminish when applied to very obese or malnourished subjects. An additional factor complicating the interpretation of BIA equations is the collinearity between the anthropometric measurements and bioimpedance. Baumgartner et al [42] showed that approximately 70% of the variance of total-body resistance was accounted for by stature, upper arm and calf circumference, and mean skinfold thickness. Nonetheless, in studies where a heterogeneous population is represented, H/R appears to be the single best predictive variable of FFM or TBW.

From a clinical point of view, FFM can be predicted from BIA with the same relative accuracy as that provided by multiple skinfold anthropometry. Kushner and Haas [43] compared the prediction of FFM by these two methods in 80 adult patients with a body mass index ranging from 12.7 to 51.1 kg/m². Highly significant correlation coefficients (r > 0.92) were seen for all subgroups of patients with a mean difference between techniques of <1 kg or 1% error. A similar agreement between methods was seen by Campos et al [44] in their study of 18 healthy adult volunteers.

**Measurement of Changes in Body Composition**

All of the studies reviewed thus far have validated the application of BIA in weight-stable subjects. The use of this technique to determine change in body composition has been examined by several investigators. For the purpose of this discussion, BIA studies measuring change in body composition have been classified into acute (within-day), intermediate (1–2 days), and long-term (weekly) investigations.

Acute changes in body water have been assessed using either an in vitro model or by evaluating dialytic patients before and after fluid removal. Using an in vitro model of narrow-bore dialysis tubing and normal saline, Meguid et al [45] confirmed that electrical resistance decreases with increasing volume of normal saline as predicted from equation 3. This observation was supported in vivo by Böhm et al [46] who measured changes in TBW in 38 patients undergoing hemodialysis. BIA determinations performed 10 minutes before and 10 minutes after dialysis were compared to the amount of fluid extracted during the procedure. Overall, there was agreement between measured and predicted changes in TBW with a correlation coefficient of 0.99. In a similar pre- and postdialysis experimental design, Kurtin et al [47] found a fair correlation (r = 0.74) between mean BIA predicted change in TBW (2.6 L) and change in body weight (2.3 kg). As discussed later, however, whole-body impedance is not sensitive enough to accurately detect fluid changes occurring in peritoneal dialysis.

In an intermediate study, Deurenberg et al [48] compared the predicted change in FFM by BIA and hydroden-
sitometry in 12 healthy volunteers who consumed a very-low-calorie diet for 2 days. The mean change in FFM as determined by densitometry (1.2 kg) was not significantly different from mean body weight change (1.3 kg). However, mean loss in FFM as calculated by three different impedence equations consistently underestimated measured weight changes. Although TBW was not directly measured in conjunction with densitometry, this study suggests that the BIA method may be imprecise to small changes in body composition.

In a long-term study, Gray [49] obtained daily measurements of R, Xc and Z in six obese females during a 2-week fast in addition to measuring deuterium-derived TBW (D_2O-TBW) prior to and after the fast. Mean weight loss was 10 kg or 8% of initial body weight. All three impedance indices increased during the fast in accordance with diminishing body water. Furthermore, the change in TBW was proportional to the change in H^2/R in the five less obese subjects (r = 0.94, SEE = 0.7 L).

Using the same reference method, Kushner et al [50] evaluated whether BIA could determine changes in TBW during longer-term weight loss. Twelve obese females consumed a hypocaloric diet for 7-19 weeks resulting in a mean weight loss of 1.16 kg/week. Body composition was measured by D_2O-TBW. BIA and skinfold anthropometry at baseline and at 5% decrements in weight. Highly significant correlations were obtained between D_2O and BIA (r = 0.97) and between D_2O and anthropometry (r = 0.93). As seen in Figure 5, individual determinations followed the line of identity with an accuracy and precision of 0.23 and ±1.43 kg, respectively. Finally, Ross et al [51] compared BIA and anthropometry with dFFM in 17 mildly obese males who underwent a 10-week diet and exercise program resulting in a mean weight loss of 5.9 kg. De-

<table>
<thead>
<tr>
<th>Study</th>
<th>n (M/F)</th>
<th>Age (yrs)</th>
<th>Reference Method</th>
<th>Variables</th>
<th>R^2</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Davies et al [30]</td>
<td>26 (12/14)</td>
<td>5-18</td>
<td>H^2O-TBW</td>
<td>M/R</td>
<td>0.94</td>
<td>1.69</td>
</tr>
<tr>
<td>Cordain et al [31]</td>
<td>30 (14/16)</td>
<td>9-14</td>
<td>dFFM</td>
<td>H^2/R</td>
<td>0.69</td>
<td>4.08</td>
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<tr>
<td>Deurenberg [32]</td>
<td>73 (33/31)</td>
<td>8-11</td>
<td>dFFM</td>
<td>H^2/R,W,G</td>
<td>0.89</td>
<td>1.31</td>
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<td>Houkkooper et al [33]</td>
<td>94 (55/39)</td>
<td>10-14</td>
<td>D-O-TBW &amp; dFFM</td>
<td>H^2/R,W</td>
<td>0.92</td>
<td>2.00</td>
</tr>
<tr>
<td>Fjeld et al [34]</td>
<td>30 (NS)</td>
<td>0.4-3</td>
<td>H^4O-TBW</td>
<td>H^2/Z,W</td>
<td>0.96</td>
<td>0.23</td>
</tr>
<tr>
<td>Deurenberg et al [35]</td>
<td>39 (18/21)</td>
<td>7-9</td>
<td>dFFM</td>
<td>H^2/R</td>
<td>0.85</td>
<td>1.07</td>
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<td></td>
<td>91 (71/20)</td>
<td>10-12 (F)</td>
<td>dFFM</td>
<td>H^2/R,W,H</td>
<td>0.96</td>
<td>1.87</td>
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<tr>
<td></td>
<td>116 (44/75)</td>
<td>13-25 (M)</td>
<td>dFFM</td>
<td>H^2/R,W,G,H</td>
<td>0.94</td>
<td>2.55</td>
</tr>
<tr>
<td>Danford et al^1</td>
<td>26 (11/15)</td>
<td>5-9</td>
<td>D_2O-TBW</td>
<td>H^2/R,W,Xc</td>
<td>0.98</td>
<td>0.58</td>
</tr>
<tr>
<td>Deurenberg et al [29]</td>
<td>166 (NS)</td>
<td>7-15</td>
<td>dFFM</td>
<td>H^2/R,W,H,G</td>
<td>0.97</td>
<td>1.68</td>
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</table>

See: Table 2 footnote for definition of terms

^1 Submitted for publication

Table 4. Selected Equations for the Prediction of Total Body Water (TBW) and Fat-Free Mass (FFM) from the Impedance Index, H^2/R

<table>
<thead>
<tr>
<th>Study</th>
<th>Equation</th>
<th>Age (yrs)</th>
<th>Gender</th>
<th>r</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBW</td>
<td>0.67 H^2/R + 0.48</td>
<td>0.4-3</td>
<td>M,F</td>
<td>0.98</td>
<td>0.36</td>
</tr>
<tr>
<td>Danford et al^1</td>
<td>0.65 H^2/R + 0.71</td>
<td>5-9</td>
<td>M,F</td>
<td>0.94</td>
<td>0.76</td>
</tr>
<tr>
<td>Davies et al, [30]</td>
<td>0.60 H^2/R + 0.5</td>
<td>5-18</td>
<td>M,F</td>
<td>0.97</td>
<td>1.69</td>
</tr>
<tr>
<td>Lukasi et al [10]</td>
<td>0.63 H^2/R + 2.0</td>
<td>19-42</td>
<td>M</td>
<td>0.95</td>
<td>2.09</td>
</tr>
<tr>
<td>Kushner &amp; Schoeller [18]</td>
<td>0.69 H^2/R + 0.8</td>
<td>19-65</td>
<td>M,F</td>
<td>0.97</td>
<td>2.50</td>
</tr>
<tr>
<td>FFM</td>
<td>0.82 H^2/R + 0.86</td>
<td>7-15</td>
<td>M,F</td>
<td>0.97</td>
<td>2.56</td>
</tr>
<tr>
<td>Deurenberg [29]</td>
<td>0.82 H^2/R + 1.0</td>
<td>7-25</td>
<td>M,F</td>
<td>0.98</td>
<td>3.03</td>
</tr>
<tr>
<td>Deurenberg [35]</td>
<td>0.81 H^2/R + 6.86</td>
<td>9-14</td>
<td>M,F</td>
<td>0.83</td>
<td>4.08</td>
</tr>
<tr>
<td>Cordain [31]</td>
<td>0.83 H^2/R + 4.43</td>
<td>10-14</td>
<td>M,F</td>
<td>0.94</td>
<td>2.60</td>
</tr>
<tr>
<td>Houkkooper et al [33]</td>
<td>0.77 H^2/R + 4.91</td>
<td>16-83</td>
<td>M,F</td>
<td>0.93</td>
<td>3.87</td>
</tr>
<tr>
<td>Deurenberg [29]</td>
<td>0.85 H^2/R + 3.04</td>
<td>19-42</td>
<td>M</td>
<td>0.98</td>
<td>2.61</td>
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<tr>
<td>Lukasi et al [10]</td>
<td>0.81 H^2/R + 6.39</td>
<td>19-50</td>
<td>M,F</td>
<td>0.98</td>
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<td>Deurenberg [28]</td>
<td>0.67 H^2/R + 3.9</td>
<td>60-83</td>
<td>M,F</td>
<td>0.94</td>
<td>3.10</td>
</tr>
</tbody>
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It is apparent from Figure 3 that R of the whole body is primarily determined by the combined R from the arm and leg. Since a significant portion of the lean compartment is represented by the extremities, measurement of the conductive volume of the arm and/or leg alone could theoretically be used to estimate FFM. In a study of 126 men and women aged 18–63 years, Chumlea et al. [52] found that the conductive volume of the arm (length\(^{1/3}\) / \(R_{\text{arm}}\)) yielded a high correlation with dFFM \((r = 0.93)\) with a SEE of 4.25 kg. This was comparable, although slightly inferior to the regression of dFFM on whole-body impedance \((r = 0.95, \text{SEE} = 3.65 \text{ kg})\). In contrast, Patterson et al. [5,53] observed that multisite segmental impedance measurements gave a better prediction of weight (or TBW) change in 11 patients undergoing hemodialysis than whole-body impedance \((r = 0.87 \text{ vs } r = 0.64)\).

Changes in thoracic and abdominal fluid volume, such as occurs in congestive heart failure, ascites or peritoneal dialysis, may also be more accurately measured using the segmental approach compared to the whole-body technique. Kurtin et al. [47] recently showed that whole-body R was insensitive to detecting the drainage of peritoneal dialysate in 5 patients. Similarly, Gugliemini et al. [54] recorded whole-body R and Xc in 10 cirrhotic patients with ascites before and immediately after paracentesis. Although the volume of intraperitoneal fluid removed was 7.9 ± 3.8 L, BIA detected an average volume change of only 1.9 ± 1.0 L. It is apparent from these 2 studies that whole-body BIA is not adequate for measuring fluid that is localized in the abdomen. Additional research and validation studies are needed to explore the utility of the segmental impedance method to measure body composition and changes in hydration status.

**Measurement of Body Water Compartments**

Total body water is distributed between two compartments: extracellular water (ECW) and intracellular water (ICW). These compartments normally constitute 38–46% and 50–58% of TBW, respectively. The distribution of TBW among these compartments will vary depending on percentage body fat and degree of malnutrition. (ECW/ICW ratio increases with severity of malnutrition.) Additionally, medical conditions associated with overhydration, i.e., increased TBW, are primarily due to an increase in ECW. Thus, estimation of these compartments may assist the clinician in the initial evaluation of the patient and improving medical and nutritional therapies.

As discussed in the section on Physical Principles, whole-body reactance is theoretically a measure of the quantity of cell membrane Xc and therefore an index of body cell mass. Whereas whole-body R primarily measures TBW, Xc may provide an estimate of the ECW/ICW ratio. In an abstract, Segal et al. [55] reported that Xc correlated...
strongly with this ratio and was a sensitive discriminator between subjects with normal body water distribution and those with abnormal overhydration. The authors found that Xc decreased with increasing ECW/ICW ratios. In another study of 64 patients, 41 of whom were malnourished, McDougall and Shizgal [56] reported that the ratio of exchangeable sodium to exchangeable potassium (an index of ECW/ICW) was also inversely related to Xc.

These initial observations were confirmed by Lukaski and Bolonchuk [23] in a cross-validation study with 110 healthy volunteers. Using multiple regression analysis, the impedance variables H²/R, W and H²/Xc were the best predictors of ECW as measured by bromide dilution (r = 0.94, SEE = 0.98). When the influence of TBW was controlled by partial correlation analysis, the relationship between ECW and Xc was strengthened. These results support the hypothesis that Xc is a potentially useful impedance variable for the estimation of the ECW and ICW compartments.

**Multifrequency Methods**

The experimental and clinical studies reviewed herein have utilized BIA analyzers that measure R and Xc at a single fixed 50 KHz frequency. However, as seen in Figure 2, the impedance of an alternating current applied to biological tissue is frequency dependent. That is, when a low frequency voltage is applied, current flows mainly through the ECW due to the large Xc of the cell membrane. At higher frequencies, the cellular membranes are crossed by the electrical current and both ECW and ICW compartments are measured [57]. By utilizing phase sensitive multifrequency electronics which generate radio frequencies from 1 KHz to 1 MHz, information about the distribution of the body water compartments can be obtained. The Xitron 4000 multifrequency bioimpedance analyzer (Xitron Technologies, San Diego, CA) is presently being marketed only for research. However, the application of dual frequency devices was initially studied over 20 years ago. Jenin et al [58] observed that at low frequencies of <5 KHz, extracellular fluid volume was a linear function of H²/Z. Moreover, the ratio of the impedance measured at 5 KHz to that measured at 1 MHz (Z₁MHz/Z₁MHz) corresponded to the ratio of TBW to ECW (TBW/ECW), yielding a ratio of 1.50 ± 0.05 in healthy young adults. Subsequently, in an animal model study of nine rabbits similar in size to premature and term infants, Espejo et al [59] found a high correlation (r = 0.95) between ECW and the impedance index L²/Z measured at 1 KHz. In a recently published study, Segal et al [60] measured whole-body R and Xc in 36 healthy men using a trifrequency bioimpedance analyzer (Tri-Frequency TV-10, Daninger Medical Technology, Columbus, OH) along with ECW and TBW determined by isotope dilution. Whereas ECW was best predicted by the variables H²/R and W measured at 5 kHz (r = 0.93, SEE = 1.94 L), TBW was best predicted by H²/R and W measured at 100 kHz (r = 0.95, SEE = 2.64).

In a series of studies conducted by Tedner et al [61–64], they demonstrated that fluid volume changes during hemodialysis or intravenous infusion could be more accurately detected by measuring the change in impedance at two frequencies (Z₁MHz and Z₁00 KHz) compared to using a single frequency. Furthermore, the impedance value showed larger changes at 1.5 KHz than at 150 KHz, indicating that the main part of the fluid removed or added was from the extracellular space. Although dual- or multifrequency instruments detect changes in fluid compartment volumes, measurement of absolute changes may not be as accurate.

**SUMMARY AND CONCLUSIONS**

BIA offers a variety of applications for the noninvasive measurement of body composition, TBW, and compartmentalization of body fluids. BIA has been validated by many investigators and is extensively used for the assessment of TBW and FFM in healthy adults and children. Its utility in estimating body composition and body fluids in hospitalized patients is currently being evaluated [65–70]. At present, the clinical usefulness of BIA to detect acute or chronic changes in body composition is limited due to altered hydration of the lean body mass, localized fluid accumulation or loss, and inability to accurately assess the distribution of water between the ICW and ECW compartments [71]. The development of new approaches, such as segmental impedance and multifrequency analyzers, should greatly expand its clinical application. For BIA to be used effectively, the user must be familiar with the principles and appropriate application of the technique.

**REFERENCES**

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