Applications of bioelectrical impedance analysis for body composition to epidemiologic studies\textsuperscript{1–4}

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ABSTRACT Bioelectrical impedance analysis (BIA) is a promising tool in the evaluation of body composition in large population studies because it is fast, is inexpensive, and does not require extensive operator training or cross-validation. The empiric nature of the relation between resistance and reactance measured by BIA and body composition has led to the development of equations that translate the raw data into liters of body water or kilograms of fat-free mass (FFM) or fat mass. These equations may not be easily transferred from one population to another if the populations differ significantly in important determinants of body composition such as age, obesity, and illness. I review two recent studies from the Framingham Heart Study in which BIA was first compared with dual-energy X-ray absorptiometry (DXA) as a validation technique, and then compared with the body mass index (BMI, in kg/m\(^2\)) as an alternative estimate of body fat. BIA was a good predictor of DXA-derived FFM \((r = 0.85-0.88, P < 0.001)\) and was superior to BMI as an estimator of body fat. \textit{Am J Clin Nutr} 1996;64(suppl):459S–62S.

KEY WORDS Body composition, lean body mass, obesity, aging, population studies

INTRODUCTION Bioelectrical impedance analysis (BIA) has great potential as a tool for assessing the body composition of populations. For this potential to be realized, convincing evidence must be presented that\textit{ 1)\textsuperscript{1} }is sufficiently precise and accurate to offer valid body-composition measurements when used in such epidemiologic settings, and \textit{2)\textsuperscript{2}} is superior to currently available techniques. I summarize the results of two recently completed studies in the Framingham Heart Study (FHS) and the Framingham Offspring Study (FOS) populations that address the use of BIA in studying body composition in the elderly (1; R Roubenoff, DP Kiel, MT Hanan, GE Dallas, PWF Wilson, TB Harris, unpublished observations, 1996). These studies addressed these two points first by validating BIA in the elderly through use of dual-energy X-ray absorptiometry (DXA) as a validation method, and second by comparing BIA with the body mass index (BMI) as a measure of fat mass.

STUDY ONE: VALIDATION OF BIA IN THE ELDERLY

Study population

Body composition was measured in conjunction with the 22nd biennial examination cycle (1992–1993) of the FHS. Of the original 5209 FHS participants, 863 survivors attended this examination cycle; the average age of these subjects was 78 y (range: 72–92 y). This study included only ambulatory subjects, 99% of whom were white. The data presented here are those obtained for the first 466 participants of this cycle. Eleven subjects were excluded because of incorrect electrode use, leaving 455 subjects for analysis. The current sample is representative of the cohort and is identical in sex proportion, age structure, and race to the remaining members of the cohort.

Body-composition measurements

Height was measured to the nearest 0.64 cm (0.25 in) by using a stadiometer. Weight was measured with subjects wearing robes and without shoes, by using a standing beam balance, to the nearest 0.11 kg (0.25 lb), in keeping with practices of previous examination cycles. English measures were converted to metric by a computer program after data entry. BIA was carried out by using a standard tetrapolar technique according to the manufacturer’s instructions (BIA-101; RJL Systems, Detroit). The instrument was calibrated weekly with a 500-\(\Omega\) resistor as recommended by the manufacturer. DXA was performed with a DPX-L whole-body scanner in fast mode at 150 mA (Lunar Corp, Madison, WI). The manufacturer’s acquisition and analysis software (version 1.3) was used to produce measures of bone, soft tissue lean mass, and fat mass (Lunar Corp).

Data analysis

Fat-free mass (FFM) was calculated in three ways: from DXA to provide a standard of comparison (FFM\textsubscript{DXA}), from BIA through use of published equations (FFM\textsubscript{BIAPUB}), and from BIA with a new equation derived from the current study.

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\textsuperscript{2}The contents of this publication do not necessarily reflect the views or policies of the US Department of Agriculture nor does mention of trade names, commercial products, or organizations imply endorsement by the US Government.

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population (FFM\textsuperscript{BIA\textsubscript{NEW}}). FFM\textsubscript{DXA} was calculated as the sum of bone mass plus soft tissue FFM derived from the DXA measurements. FFM\textsubscript{BIA\textsubscript{PUB}} was calculated from height/resistance, reactance, weight, and sex with the following equation of Lukaski et al (2, 3):

$$
\text{FFM (kg)} = -4.03 + 0.734(\text{Ht}^2/R) + 0.116(\text{weight})
+ 0.096(X_c) + 0.984(\text{Sex}) \quad (1)
$$

where \(\text{Ht}\) is height in cm, \(R\) is resistance in \(\Omega\), weight is in kg, \(X_c\) is reactance in \(\Omega\), and \(\text{sex} = 0\) for women and 1 for men. The published equation was derived in a population with a mean age of 27 y (range: 18–50 y), a mean body fat percentage of 16.2\% in men and 25.1\% in women, a mean resistance of 432.4 \(\Omega\) in men and 559.7 \(\Omega\) in women, and a mean reactance of 60.4 \(\Omega\) in men and 64.9 \(\Omega\) in women. The validation method for the published equation was hydrodensitometry (2).

FFM\textsubscript{BIA\textsubscript{NEW}} was derived from an initial study population with using multiple linear regression to regress FFM\textsubscript{DXA} on height/resistance (with height expressed in cm), reactance, and weight (expressed in kg) separately for men and for women (BMDP statistical software, version 7, 1992; SPSS, Inc, Chicago). FFM\textsubscript{BIA\textsubscript{PUB}} and FFM\textsubscript{BIA\textsubscript{NEW}} were then compared with each other by plotting the result for each subject in the population against that subject’s FFM\textsubscript{DXA}. Men and women were analyzed both separately and together. The SD of the mean and the SEE (equal to the SD of the mean difference between methods) for each plot were taken as measures of precision, and the difference between means and the correlation \((r)\) between FFM\textsubscript{DXA} and each FFM derived from BIA were taken as measures of accuracy.

**Results**

The characteristics of the body composition of the study population from FHS and the young reference population are shown in **Table 1**. The accuracy and precision of the new equation in predicting FFM was compared with a published equation derived in the younger population. The new equation improved accuracy, reducing the mean difference in FFM between BIA and DXA to 0 kg compared with 2.13 kg in men \((P < 0.01)\) and 2.64 kg in women \((P < 0.0001)\), as expected when an equation is developed and applied in the same population. Thus, the equations developed in young people overestimated FFM by 4\% in men and 7.1\% in women. However, the new equation did not improve the precision of BIA, in that the SEE was virtually unchanged (3.43 kg in men and 2.09 kg in women), as was the correlation between BIA and DXA \((r = 0.85\) in men and 0.88 in women with both equations). Most importantly, the new equation eliminated a size-related discrepancy between FFM measured by DXA and FFM measured by BIA based on the published equation developed in younger adults. This discrepancy is shown in **Figure 1**, in which the difference between FFM by the two methods is plotted versus quartile of FFM measured by DXA. The mean difference in FFM between the two methods increases by quartile of FFM for both men and women with the published equation \((P < 0.01)\) compared with zero difference, whereas the new equation shows no such bias.

**Comments**

In this study, we developed specific BIA equations for men and women over the age of 70 y by using DXA as the reference method. We applied these equations to the population from which they were derived to calculate their precision and accuracy. These results were then compared with values of FFM calculated from a published BIA equation derived in an external population. The external population differed from the study population in age, fatness, resistance, and reactance. Although there was an improvement in the precision and accuracy of FFM with the use of the population-specific equation, the improvement was small. However, the systematic overestimation of FFM that occurred with the published equation was eliminated by the new equation.

This approach maximizes the performance of BIA by comparing the new equation with the reference method under the ideal situation of the same population, so that the results show the best that can be expected of BIA in the elderly. It may be unrealistic to expect better performance of BIA in the elderly in comparison with a method like DXA than a correlation of 0.85 in men and 0.88 in women and an SEE of 2.09 kg in women and 3.43 kg in men. This leads to a coefficient of determination \((R^2)\) of 0.72–0.77. Most of the remaining error in using BIA is due to the assumptions inherent in the technique, such as the oversimplification of the shape of the human body as a cylinder, the reliance on total body water as the measure of FFM \((3–5)\), and the use of a two-compartment model \((4)\).

**Table 1**

Study one: characteristics of the study populations

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Male ((n = 161))</th>
<th>Female ((n = 294))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>78.2 ± 4.3\textsuperscript{2}</td>
<td>78.4 ± 4.5\textsuperscript{2}</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>86.0 ± 12.1\textsuperscript{2}</td>
<td>63.8 ± 11.9\textsuperscript{2}</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>182.4 ± 7.3</td>
<td>153.4 ± 6.6</td>
</tr>
<tr>
<td>BMI (kg/m\textsuperscript{2})</td>
<td>26.0 ± 3.7</td>
<td>27.1 ± 4.7</td>
</tr>
<tr>
<td>Resistance ((\Omega))</td>
<td>432.4 ± 59.2</td>
<td>555.9 ± 70.0</td>
</tr>
<tr>
<td>Reactance ((\Omega))</td>
<td>60.4 ± 15.4</td>
<td>50.3 ± 12.4</td>
</tr>
<tr>
<td>FFM (kg)</td>
<td>71.5 ± 6.7</td>
<td>37.2 ± 4.4</td>
</tr>
<tr>
<td>Fat (%)</td>
<td>16.2 ± 7.0</td>
<td>40.6 ± 7.6</td>
</tr>
</tbody>
</table>

\textsuperscript{1}\text{\(\bar{x}\) ± SD. FHS, Framingham Heart Study population; Young, younger population in whom the published equation was derived; FFM, fat-free mass.}

\textsuperscript{2}\text{99\% CIs around the sex-specific group means for these characteristics overlap.}

\textsuperscript{3} Determined by reference methods of dual-energy X-ray absorptiometry in the elderly population and underwater weighing in the young population.
RESULTS

There were 927 men and 1105 women available for analysis, with mean (± SD) ages of 56.4 ± 12.2 and 58.9 ± 13.6 y, respectively. The subjects tended to be overweight, with both BMI and percentage fat above US medians (7).

Ignoring age, there was a quadratic relation between BMI and percentage fat for both men and women. BMI itself explained 55% of the variability in percentage fat in women \( (P < 0.0001) \) and only 38% of the variability in men \( (P < 0.0001) \). The quadratic term, BMI\(^2\), explained an additional 5.5% of the variability in percentage fat in women \( (P < 0.001) \) and a small but still significant 0.5% in men \( (P < 0.01) \). The SEE of percentage fat with BMI and BMI\(^2\) was 4.8 percentage points in the men and 5.0 percentage points in the women, indicating that the estimate of fatness based on BMI is imprecise. When age was grouped by decades and entered along with BMI and BMI\(^2\) in regression analyses for the outcome of percentage fat, age altered the relation between BMI and percentage fat in the women \( (F_{1,15,1087} = 5.22, P < 0.000001) \), and less so in the men \( (F_{1,12,912} = 1.94, P < 0.027) \).

In a subset of 583 FHS subjects in whom both DXA and BIA were performed, we tested the additional usefulness of BMI over BMI in predicting body fat measured by DXA (Table 2). In this group, BMI alone was associated with fat weight to a greater extent than in the larger data set \( (R^2 = 0.72, \text{SEE} = 4.6 \text{ kg}, P < 0.0001) \). When fat estimated by BIA was added to BMI in a linear regression model, the association improved significantly \( (R^2 = 0.84, \text{SEE} = 3.47 \text{ kg}, P < 0.0001) \). These results were also seen when the data from men and women were analyzed separately.

**TABLE 2**

<table>
<thead>
<tr>
<th>Variable (^1)</th>
<th>( \beta )</th>
<th>( \text{SE} (\beta) )</th>
<th>Model ( R^2 )</th>
<th>( \text{SEE} )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>-19.41</td>
<td>1.15</td>
<td>0.723</td>
<td>4.62</td>
</tr>
<tr>
<td>BMI (kg/m(^2))</td>
<td>1.66</td>
<td>0.04</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td><strong>Model 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>-5.11</td>
<td>1.10</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>BMI (kg/m(^2))</td>
<td>0.47</td>
<td>0.06</td>
<td>0.844</td>
<td>3.47</td>
</tr>
<tr>
<td>Fat mass (BIA) (kg)</td>
<td>0.68</td>
<td>0.032</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

\(^1\) Model 1 includes BMI only; model 2 includes BMI plus BIA.
Comment

BMI was a poor predictor of percentage fat in both women ($R^2 = 0.55$) and men ($R^2 = 0.38$) and was imprecise (SEE = 5 percentage points). In addition, the relation between percentage body fat and BMI was quadratic in both sexes, and was altered by age in women ($P < 0.0001$) and to a lesser extent in men ($P < 0.027$). These data suggest that BIA, which can be performed in large populations, is a significant advance over the current standard for such studies, the BMI.

FUTURE RESEARCH NEEDS

The above data suggest that BIA can indeed become a useful method of measuring body composition in large epidemiologic studies. However, it is not clear whether specific BIA equations must be developed for various subgroups of such study populations. For example, it is not known whether race-specific equations for African American, Hispanic American, and Native American populations would significantly improve the accuracy of BIA in these groups. Another important research arena is the one suggested by our finding that even under idealized study conditions of developing a formula and then applying it in the same study population, the coefficient of determination of BIA ($R^2$) is no better than 0.88. This suggests that the limitation of BIA rests not in the equations used to generate body composition data from raw resistance and reactance data, but rather in the assumptions inherent in the technique as currently practiced, such as the cylindrical shape of the human body and the behavior of electrical current in the body. It may be that more sophisticated treatment of these variables will be required to improve the precision and accuracy of BIA further.

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REFERENCES