Comparison of multifrequency bioelectrical impedance analysis with dual-energy X-ray absorptiometry for assessment of percentage body fat in a large, healthy population

Guang Sun, Curtis R French, Glynn R Martin, Ban Younghusband, Roger C Green, Ya-gang Xie, Maria Mathews, Jane R Barron, Donald G Fitzpatrick, Wayne Gulliver, and Hongwei Zhang

ABSTRACT
Background: Bioelectrical impedance analysis (BIA) is widely used in clinics and research to measure body composition. However, the results of BIA validation with reference methods are contradictory, and few data are available on the influence of adiposity on the measurement of body composition by BIA.

Objective: The goal was to determine the effects of sex and adiposity on the difference in percentage body fat (%BF) predicted by BIA compared with dual-energy X-ray absorptiometry (DXA).

Design: A total of 591 healthy subjects were recruited in Newfoundland and Labrador. %BF was predicted by using BIA and was compared with that measured by DXA. Methods agreement was assessed by Pearson's correlation and Bland and Altman analysis. Differences in %BF among groups based on sex and adiposity were analyzed by using one-factor analysis of variance with Bonferroni correction.

Results: Correlations between BIA and DXA were 0.88 for the whole population, 0.78 for men, and 0.85 for women. The mean %BF determined by BIA (32.89 ± 8.00%) was significantly lower than that measured by DXA (34.72 ± 8.66%). The cutoffs were sex specific. BIA overestimated %BF by 3.03% and 4.40% when %BF was <15% in men and <25% in women, respectively, and underestimated %BF by 4.32% and 2.71% when %BF was >25% in men and >33% in women, respectively.

Conclusions: BIA is a good alternative for estimating %BF when subjects are within a normal body fat range. BIA tends to overestimate %BF in lean subjects and underestimate %BF in obese subjects.

KEY WORDS Percentage body fat, multifrequency bioelectrical impedance analysis, dual-energy X-ray absorptiometry, Newfoundland population, body composition

INTRODUCTION

Body-composition information, including percentage body fat (%BF), is widely used to evaluate growth and nutrition in children (1, 2) and nutritional status in various disease conditions, such as AIDS (3), gastrointestinal disease (4), Crohn disease (5), and renal and various other diseases (6, 7). Body-composition assessment has many clinical uses, such as assessing disease progression or treatment efficacy (3–7). Body-composition measurements are also used to assess athletes (8, 9) and can be used in the study of aging (10).

Many technologies are available to measure body composition, such as the underwater weighing method, which has been used as a traditional standard (11). Air-displacement plethysmography and dual-energy X-ray absorptiometry (DXA) are 2 relatively new reference methods (12–14). The use of these methods is limited, however, because of inaccessibility and the high cost of equipment. Thus, simple methods such as bioelectrical impedance analysis (BIA) and skinfold-thickness measurements are still the norm in field studies and for public use (15–17).

The BIA method has been widely used in clinics, in sports medicine, and in weight reduction programs (18, 19). Several studies have compared predictions of %BF by BIA with measurements made by reference methods (20–24), but the results are contradictory. Some studies showed that %BF is overestimated by BIA (25, 26), whereas others suggested that BIA underestimates %BF (27–29). Some studies showed good agreement between BIA and DXA (21, 30, 31), whereas others indicated that the BIA method lacks precision and accuracy (20, 32, 33). It seems that the error of the BIA method in comparison with reference methods is greater in patients with chronic renal failure than in healthy subjects (34). In addition, the degree of adiposity appears to influence the variation in %BF measured by BIA in children (35, 36). Questions such as whether BIA tends to over- or underestimate %BF when compared with DXA and the extent of this bias remain unanswered because most of the studies were performed with small sample sizes and in patients with different diseases.

To answer the above questions, we performed parallel measurements of %BF by using both multifrequency BIA and DXA in a large sample of the healthy population in Newfoundland and...
TABLE 1
Physical characteristics of the subjects

<table>
<thead>
<tr>
<th></th>
<th>All subjects (n = 591)</th>
<th>Men (n = 100)</th>
<th>Women (n = 491)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>42.15 ± 10.27 (19, 60)</td>
<td>39.65 ± 12.5 (19, 60)</td>
<td>42.66 ± 9.70 (19, 60)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>70.99 ± 14.68 (45, 157)</td>
<td>84.24 ± 13.53 (55, 137)</td>
<td>68.31 ± 13.41 (45, 157)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>164.24 ± 7.7 (135, 198)</td>
<td>174.99 ± 7.49 (157, 198)</td>
<td>162.07 ± 5.6 (135, 178)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>26.28 ± 4.94 (16.98, 54.27)</td>
<td>27.53 ± 4.39 (19.87, 43.53)</td>
<td>26.03 ± 5.0 (16.98, 55.27)</td>
</tr>
<tr>
<td>Waist-to-hip ratio</td>
<td>0.89 ± 0.07 (0.73, 1.24)</td>
<td>0.96 ± 0.07 (0.74, 1.20)</td>
<td>0.87 ± 0.07 (0.73, 1.24)</td>
</tr>
</tbody>
</table>

1 All values are ¯ ± SD; minimum and maximum in parentheses.
2,3 Significantly different from men (one-factor ANOVA): 2P = 0.005, 3P < 0.001.

TABLE 2
Percentage body fat measured by bioelectrical impedance analysis (BIA) and by dual-energy X-ray absorptiometry (DXA)

<table>
<thead>
<tr>
<th>Method</th>
<th>All subjects (n = 591)</th>
<th>Men (n = 100)</th>
<th>Women (n = 491)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIA</td>
<td>32.89 ± 8.00 (10.6, 58.3)</td>
<td>22.67 ± 6.12 (10.6, 37.7)</td>
<td>34.93 ± 6.73 (17.0, 58.3)</td>
</tr>
<tr>
<td>DXA</td>
<td>34.72 ± 8.66 (4.6, 59.9)</td>
<td>25.03 ± 7.17 (7.4, 41.6)</td>
<td>36.68 ± 7.55 (4.6, 59.9)</td>
</tr>
</tbody>
</table>

1 All values are ¯ ± SD; minimum and maximum in parentheses.
2 Significantly different from DXA, P < 0.001 (paired t-test).

Labrador. DXA is arguably one of the best reference methods to use: it has been validated against other methods of body composition analysis and has shown little bias based on age, sex, physical activity levels, race, or proportion of fat. BIA measurements were carried out with the subject lying in a supine position on a flat, nonconductive bed by using a multifrequency tetrapolar technique (QuadScan 4000; Bodystat, Douglas, United Kingdom). The Bodystat QuadScan 4000 unit has 4 electrodes. Two electrodes were placed on the right wrist with one just proximal to the third metacarpophalangeal joint (positive) and one on the wrist next to the ulnar head (negative). Two electrodes were placed on the right ankle with one just proximal to the third metatarsophalangeal joint (positive) and one between the medial and lateral malleoli (negative). Multifrequency (5, 50, 100, and 200 kHz) currents were introduced from the positive leads and traveled throughout the body to the negative leads. %BF was calculated by using the manufacturer’s software.

SUBJECTS AND METHODS

Subjects

All 591 subjects were recruited from the Canadian province of Newfoundland and Labrador (NL) for a large-scale genetic study of human complex diseases. Subjects were self-selected through a poster campaign advertising the project. Responders gave their written consent and then completed a screening questionnaire that included basic personal information, such as physical characteristics and health status. Persons who met the following criteria were eligible to participate in the study: age between 19 and 60 y, born in NL and family has lived in NL for ≥3 generations, and healthy without serious metabolic, cardiovascular, or endocrine disease. The study was approved by the Human Investigation Committee of the Faculty of Medicine, Memorial University of Newfoundland.

Measurements of percentage body fat

All measurements were performed after the subjects had fasted for 12 h. The subjects were weighed in standardized light clothes and without shoes on a platform manual scale balance (Health O Meter Inc, Bridgeview, IL).

DXA (Lunar Prodigy; GE Medical Systems, Madison, WI) was used for the measurement of whole-body composition, including fat mass, lean body mass (comprising muscle, internal organs, and body water), and bone mineral densities. %BF was calculated from entire body mass (including bone mineral densities) by using the manufacturer’s software (version 4.0). The subjects had undergone no nuclear examination within the previous 4 wk, and the female subjects were not pregnant at the time of examination. All metal items were removed from the volunteer to ensure accuracy of the measurement. DXA measurements were performed while the subject was lying in a supine position. BIA measurements were done immediately after the DXA analysis.

RESULTS

Physical characteristics of the subjects

The subjects’ basic physical characteristics are summarized in Table 1. A total of 591 eligible volunteers (491 women and 100 men) participated in the study. The subjects’ ages ranged from 19
to 60 y, and the men were 3.0 y younger than the women on average. The men were also 15.93 kg heavier and 12.9 cm taller than the women on average. The subjects had a wide range of body mass indexes (BMIs; in kg/m²): from 16.98 to 55.27. Waist-to-hip ratio was larger in the men.

Comparison of %BF measured by BIA and DXA

The general correlation coefficient ($r$) between the 2 methods for men and women combined was 0.88. The correlation coefficients between BIA and DXA for men and women were 0.78 and 0.85, respectively.

The results of %BF measured by both BIA and DXA are shown in Table 2. The mean %BF obtained by BIA in all subjects was significantly lower than that measured by DXA: 32.89 ± 8.00% compared with 34.72 ± 8.66%. The results were similar when the analysis was performed according to sex.

BIA bias on the basis of %BF

When the subjects were stratified according to their %BF (low, moderate, or high), significant differences in the BIA-DXA comparisons were apparent. The agreement between BIA and DXA was almost perfect when the subjects’ %BF was not low or high. As shown in Figure 1, BIA actually overestimated %BF by 3.56% for subjects whose %BF was >20% (lean). BIA underestimated %BF by 2.65% for subjects whose %BF was >30% (obese), and the 2 methods fit each other well when %BF was between 20% and 30% (normal). The cutoffs for lean and obese categories were sex specific. As shown in Figure 2 for men, BIA overestimated %BF by 3.03% when %BF was <15% (lean), underestimated %BF by 4.32% when %BF was >25% (obese), and had little difference with DXA when %BF fell between 15% and 25% (normal). As shown in Figure 3 for women, BIA overestimated %BF by 4.40% when %BF was <25% (lean), underestimated %BF by 2.71% when %BF was >33% (obese).

### Table 3

Multivariate linear regression analysis of the difference between measurements of percentage body fat by bioelectrical impedance analysis and dual-energy X-ray absorptiometry (DXA) according to adiposity and independent variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\beta \pm SE$</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DXA</td>
<td>-0.663 ± 0.019</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>BMI</td>
<td>0.639 ± 0.030</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Age</td>
<td>0.209 ± 0.009</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Sex</td>
<td>8.542 ± 0.370</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Waist-to-hip ratio</td>
<td>1.434 ± 1.543</td>
<td>0.353</td>
</tr>
</tbody>
</table>

$^1$ Model $\hat{r}^2 = 0.73, n = 591$. $\beta =$ unstandardized coefficient. For sex, male = 0, female = 1.
and had little difference with DXA when %BF fell between 25% and 33% (normal). All of these differences between groups were significant by one-factor ANOVA, except for the comparison between lean and normal-weight men. The results were corrected according to the Bonferroni method.

Multivariate regression analysis was performed to explore the role of physical variables on the adiposity-dependent bias of BIA when compared with DXA. Although variables such as BMI, age, and sex significantly contributed to the variation in %BF predicted by BIA, the influence of adiposity remained significant after adjustment for these factors (Table 3).

DISCUSSION

Body-composition information is extensively used in clinics, sports medicine, and other health-related fields (1–8). Reference methods such as DXA, air-displacement plethysmography, and underwater weighing can provide accurate results; however, these methods are costly and often inaccessible to the public (11–14). In most situations, BIA and other field methods are the only techniques available for body-composition measurements.

The results of the present study bridge the gap between previous contradictory studies and provide reliable information on the correct interpretation of %BF analysis by BIA. Our study design featured 2 aspects that improved on previous investigations. First, our sample size of 591 persons is larger than any other BIA validation study to our knowledge. Second, we covered a wider range of %BF than in previous studies, which is more representative of a healthy population. In addition, our female cohort, which comprised 491 women, is much larger than the sample size used to develop the QuadScan prediction algorithm and covers a wider range of %BF (IJ Meeuwsen, Bodystat Ltd, personal communication, 2004). Thus, we identified significant bias caused by adiposity that was not detected and considered in the development of the QuadScan 4000 prediction equation.

The correlations between BIA and DXA for %BF were generally good, which is consistent with other reports (18–28, 30, 31). The agreement between BIA and DXA was assessed by use of the Bland and Altman analysis in all subjects combined and in men and women separately. The correlation coefficient was highest when all subjects were analyzed together and was reduced when the subjects were stratified by sex. However, the correlation coefficient alone is not sufficient to prove the equivalence of the 2 methods (37). When the mean value of %BF was compared between the 2 methods, BIA always underestimated %BF in the combined subjects and in men and women separately. Although the absolute values of the mean difference between the 2 methods were small, the agreement may not be suitable for measurement of body composition in individual subjects. The Bland and Altman analysis shows that the individual variations are large, with the variation being greater in men than in women (−2.26 ± 4.62% compared with −1.80 ± 4.05%).

The major contribution of the present study is the demonstration that the size and direction of the BIA-DXA difference in adults is dependent on the %BF of the subject (low, medium, or high). BIA tends to overestimate body fat when subjects are relatively lean and underestimate body fat when subjects are overweight or obese. Furthermore, the cutoffs between these groups differ in men and women. BIA tends to overestimate body fat when %BF is <15% in men and <25% in women (lean). BIA tends to underestimate body fat when %BF is >25% in men and >33% in women (obese). These cutoffs define obesity according to %BF (38). Little difference was seen when BIA was used in men with %BF between 15% and 25% and in women with %BF between 25% and 33% (normal). These findings have important implications for the use of BIA measurements and the interpretation of results.

Multivariate linear regression analysis was performed to explore the role of physical variables on the variation in %BF measured by BIA among groups based on adiposity. Our model shows that the variation in the difference in %BF measurements by the 2 methods can be explained by adiposity, as determined by DXA. Variables such as BMI, age, and sex significantly improved the amount of explained variation in our model; however, the influence of adiposity remained significant after adjustment for these factors. We therefore conclude that the variation in predicted %BF by BIA among adiposity groups could be reduced by adjusting for adiposity, BMI, age, and sex.

In summary, parallel measurement of %BF by BIA and DXA showed that BIA analysis must be carefully interpreted when used on lean, overweight, or obese persons. BIA tends to underestimate body fat in all subjects and in men and women separately. This bias, however, depends on the degree of adiposity. In lean subjects, BIA tends to overestimate %BF. In overweight or obese subjects, BIA tends to underestimate %BF. Because BIA is used to measure body composition in a variety of clinical settings, such as in patients with AIDS wasting (3) or chronic obesity (39), this bias must be taken into consideration when interpreting BIA data.

We thank the volunteers who participated in the present study and the following persons for their contributions to volunteer recruitment and data input: Yang Zhang, Christiane Dawe, Dax Rumsey, James Thorburn, Amber Snow, Aihua Ma, Sandra Cooke, Elizabeth Drover, and Aman Gill.

GS was responsible for study design, data analysis, and writing of the manuscript. CRF was responsible for data collection, statistical analysis, and revision of the manuscript. GRM, HZ, WG, BY, RCG, and Y-GX were responsible for data collection. MM was involved in statistical analysis. GS holds the position of chair of pediatric genetics, which is supported by Novartis Pharmaceuticals. None of the other authors had any conflicts of interest to disclose.

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