ABSTRACT

Bioelectrical impedance analysis enables a rapid and safe assessment of body water. When it is assumed that the hydration factor of the fat-free mass is constant and is not different in the obese state, then fat-free mass and thus body fat can be assessed with bioelectrical impedance. However, several factors limit the valid application of bioelectrical impedance analysis in the severely obese state. One is the assumption of a constant hydration factor. Furthermore, body geometry is different in the obese state and body water distribution may also be different. All these factors have an effect on the validity of the method in the severely obese state, for which the amount of body fat generally will be underestimated with use of prediction formulas developed in normal-weight subjects. I discuss these limiting factors and provide some theoretical background. Am J Clin Nutr 1996;64(suppl):449S–52S.

KEY WORDS
Bioelectrical impedance, obesity, body fat, body composition, water distribution

INTRODUCTION

In bioelectrical impedance analysis (BIA) a small alternating current is applied to the body, and the resistance or impedance (Ω) of the body to that current is measured (1). Of the different body components, only water with its dissolved electrolytes can conduct the current (2); thus, body impedance is a measure of body water. Assuming that the body has the simple geometric shape of a cylinder, the theoretical relation between body water and impedance is of the form TBW = ρ × H^2/Z, where TBW is total body water, ρ is the specific resistivity of the body fluid, H is body height, and Z is the measured impedance value (1, 3, 4). The specific resistivity ρ of the body fluid depends on the kind and amount of dissolved electrolytes as well as on temperature. When TBW is assumed to be a fixed part of the fat-free mass (FFM), at least in normal, healthy subjects (5), BIA also enables the assessment of FFM. When body impedance is measured simultaneously with TBW (measured through use of $^3$H2O, $^3$H2O, or $^3$H2O dilution) or with FFM (measured through use of hydrodensitometry or dual-energy X-ray absorptiometry), the empirical relation between measured TBW or FFM and the impedance index (H^2/Z) is high, enabling the assessment of TBW or FFM from impedance (1, 3, 4, 6, 7). In the past 10 y many studies have been published in which the validity of the impedance method in assessing TBW or FFM was shown in specific groups. However, prediction formulas are often population specific, and prediction errors may be too large for valid individual assessment in clinical situations (8). Additionally, several factors limit the use of BIA as a valid predictor of the amount of body fat in extremely obese subjects. Some of these factors are general; others are specifically related to changes in electrical properties of the body in the obese state.

PREDICTION ERRORS RELATIVE TO BODY COMPOSITION

Differences between measured and predicted FFM and percentage body fat in relation to body mass index (BMI) in a group of 661 healthy adults are given in Table 1. The prediction formula used was developed in this specific group (7). The mean SEE for FFM from impedance was 2.6 kg, which for the total population equaled a CV of ≈5%. Although the mean prediction error was relatively small in the lean group (Table 1), the error in predicted percentage body fat was highest in this group when it was expressed as a CV. Hence, in very lean subjects, predicted percentages of body fat may have relatively large errors. In some extreme cases this could even result in a predicted FFM larger than actual body weight. With increasing body fatness (increasing BMI), both the absolute (SD, kg) as well as the relative (CV%) errors in predicted FFM increased; at very high levels of body fatness, impedance underestimated body fat.

This dependency of predicted values on the degree of body fatness was found in several studies. Segal et al (6) found that the prediction error for FFM can be lowered when different prediction formulas are used for lean and obese subjects. In a study in lean and obese women in which the validity of several methods was tested, McNeill et al (9) showed that in obese subjects body fat was underestimated by impedance. van der Kooy et al (10) showed that the overestimation of FFM from impedance with several prediction formulas from the literature was more pronounced in obese women before weight loss, and was lower or even disappeared after weight loss. Lukaski (11), using dual-energy X-ray absorptiometry as the reference technique, showed a negative relation between residuals of predicted FFM and percentage body fat.

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TABLE 1
Difference between measured (densitometry) and predicted (bioelectrical impedance analysis) fat-free mass (FFM) and percentage body fat (BF%) in groups with different BMIs

<table>
<thead>
<tr>
<th>BMI (kg/m²)</th>
<th>FFM</th>
<th>CV</th>
<th>BF%</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 18 (n = 8)</td>
<td>-0.3 ± 1.9</td>
<td>4.4</td>
<td>0.3 ± 3.4</td>
<td>19.1</td>
</tr>
<tr>
<td>18–20 (n = 96)</td>
<td>-0.2 ± 2.0</td>
<td>4.4</td>
<td>0.8 ± 3.7</td>
<td>18.2</td>
</tr>
<tr>
<td>21–25 (n = 406)</td>
<td>0.1 ± 2.6</td>
<td>4.9</td>
<td>-0.2 ± 3.7</td>
<td>15.7</td>
</tr>
<tr>
<td>26–30 (n = 101)</td>
<td>0.0 ± 2.8</td>
<td>5.1</td>
<td>0.3 ± 3.3</td>
<td>9.9</td>
</tr>
<tr>
<td>31–33 (n = 31)</td>
<td>0.5 ± 4.1</td>
<td>7.2</td>
<td>-0.3 ± 3.6</td>
<td>9.6</td>
</tr>
<tr>
<td>34–35 (n = 13)</td>
<td>-0.5 ± 4.1</td>
<td>7.4</td>
<td>0.8 ± 4.0</td>
<td>10.3</td>
</tr>
<tr>
<td>&gt; 35 (n = 6)</td>
<td>-3.6 ± 4.5</td>
<td>8.3</td>
<td>3.5 ± 4.3</td>
<td>9.1</td>
</tr>
</tbody>
</table>

1 The prediction formula used was developed in the whole group and was as follows: FFM = (3400 H²/Ro) + 1534 H + 0.237 W - 0.127 where H is body height (m), Ro is resistance (Ω) at 50 kHz, W is weight (kg), age is in years, and sex is 0 for females and 1 for males (7).

2 Mean error.

The bias in predicted FFM and the increasing individual error at higher BMIs indicate a large biological variability in the relation between body composition and body impedance. This variability can be due to violations of assumptions in the reference method in obese subjects, as well as to changes in electrical properties of tissues in the obese state. The following factors affect the validity of the bioelectrical impedance method in the obese state: increased relative TBW (body fat is underestimated), different body geometry (body fat is overestimated), and increased relative extracellular water (body fat is underestimated).

VIOLATIONS OF ASSUMPTIONS

Bioelectrical impedance is a measure of body water (2). In formulas for predicting FFM from impedance, it is assumed that the hydration of the FFM is a constant factor, normally 73.2% in adults (5). Apart from normal biological variation in hydration (5, 12–14), there are strong indications that the relative amount of water in the FFM may be higher in obese subjects (15). When prediction formulas developed in normal-weight subjects are applied to obese subjects in whom the water fraction in the FFM is > 73%, FFM is overestimated and thus body fat is underestimated. Whether there is an overhydration of FFM in the obese state surely depends not only on the level of body fatness, but also on individual characteristics. This explains the larger individual errors found in obese compared with normal-weight subjects, as shown also in Table 1 (6, 7, 9).

EFFECT OF BODY BUILD

The body build of obese subjects is different from that of lean subjects. Several investigators have reported the disproportionate impedance values of the trunk and extremities: the trunk has about one-half of the conductive mass but contributes only 10–20% to total body impedance (16–18). This phenomenon can be attributed to the fact that the trunk is relatively short and has a large diameter (impedance is proportional to length and inversely proportional to diameter). In obese subjects, in whom relatively more water (and therefore FFM) will be located in the trunk, the effect of that part of body water on total body impedance will be low. Thus, total body impedance is likely to be high compared with the amount of body water; hence, the prediction of TBW or FFM will be biased toward values that are too low (Figure 1). This is especially the case in those with abdominal obesity. To my knowledge, there are no reported impedance data in the literature in very obese subjects in relation to lean subjects. However, the fact that the amount of water loss predicted through use of impedance in ascites patients is only part of actual weight loss shows the importance of body geometry (19, 20). The bias in FFM of the six obese subjects in Table 1 increased from 3.5 to 4.1 kg FFM when residuals were corrected for the plumper body build (FFM/height) of the obese subjects, also showing the effect of body build on body impedance values.

EFFECT OF BODY WATER DISTRIBUTION

Obese subjects are likely to have a different body water distribution from lean subjects. Waki et al (15) showed that the relative ratio of extracellular water to TBW was higher in obese subjects. This effect was more pronounced at higher BMIs. Multifrequency BIA shows that at the often-used frequency of 50 kHz, the current does not fully penetrate the cell membrane (Figure 2) (21). This means that measured impedance at 50 kHz is not a measure of TBW but a measure of extracellular water plus partly intracellular water. Thus, the empirical relation between TBW (FFM) and the impedance index depends on body water distribution: in subjects with a relatively high amount of extracellular water, TBW (FFM) will be overestimated by formulas developed in a population with a normal distribution of body water. In fact, the effect of sex and age on the relation between FFM and the impedance index could be explained by sex and age differences in body water distribution (7).

When multifrequency impedance scans are modeled, the theoretical intracellular and extracellular resistance can be calculated by extrapolation (21, 22). From the scarce data in the literature currently, it can be concluded that despite the larger amount of intracellular than extracellular water in the body, intracellular resistance is higher than extracellular resistance (21, 22). This may be due to the capacitative resistance of the cell membrane, to differences in kind and amount of dissolved electrolytes in the two body water compartments, or both. The higher specific resistivity of the intracellular fluid results in a dependency of TBW (FFM) predicted from the impedance.

![Figure 1](https://academic.oup.com/ajcn/article-abstract/64/3/449S/4651639/4651639)
index on body water distribution, an effect that is independent of whether the current fully penetrates the cell membrane (21).

These two factors, an incomplete conductance of the current at 50 kHz and a higher specific resistivity of intracellular water, can cause a remarkable and systematic overestimation of TBW or FFM from impedance measurements in severely obese subjects. In the studies of weight loss described in the literature, the loss of TBW or FFM was not always predicted with validity, but many of the conflicting results can be explained by changes in water distribution during weight loss or by differences in body water distribution at the time of measurement (10, 23–28). When the impedance data published by Gray (23) are reanalyzed, it can be seen that there are no apparent changes in impedance during the first days of the weight-loss period (Figure 3). This is in accordance with data of Deurenberg et al (24), who showed that 24 h of fasting did not result in a change in impedance despite a water-weight loss of ~1.2–1.3 kg. These observations can be explained by the fact that impedance at 50 kHz does not (fully) penetrate the cell membrane; thus, it cannot measure the loss of intracellular water (water bound to glycogen) that occurs during the first days of weight loss. However, when the current can penetrate the cell membrane, the increase in impedance as the result of intracellular water loss should be less then expected from water loss because the specific resistivity of the body fluid decreases with the loss of intracellular water.

The differences in impedance change with a comparable weight loss in the studies of van der Kooy et al (10) and Deurenberg et al (25) are probably due to the fact that in the first study impedance was measured 3 wk after the weight loss had occurred, thus, after glycogen stores were recovered again. In this situation a “normal” distribution of body water, and thus a “normal” specific resistivity of the body fluids, can be expected. In the study by Deurenberg et al (25), impedance was measured immediately after weight loss. In this situation the specific resistivity of the body fluid is lower; thus, an increase of total body impedance by the water loss is counteracted.

**INDIVIDUAL MEASUREMENTS**

The day-to-day variability of impedance measurements is ~10–15 Ω, which corresponds with a CV of ~1–2% (1, 4, 29). The between-observer variability in impedance measurements is 5–7 Ω (30, 31). Correlations for the variation in body weight lowers the CV% slightly (32). The exact placement and replacement of electrodes is important (32).

Depending on the prediction formula used [in which the regression coefficient for impedance (impedance index) ideally must be high], a variability of 10–15 Ω equals an amount of TBW or FFM of 1.5–2 or 2–3 kg, respectively. This variability means that, regarding of eventual changes in body water, body water distribution, and body build, changes less than this amount cannot be detected reliably in an individual. Inclusion of body weight in formulas used to predict changes in body water or FFM is not appropriate because body weight changes are then automatically attributed to a fixed part of body water or FFM changes.

When changes in body water distribution occur, an expected increase in body impedance (due to water loss) can be partly or even completely counteracted. The opposite can also be true. Two typical examples are the loss of intracellular water (bound to glycogen) after a short time of fasting that does not coincide with an increase in impedance (24). Furthermore, after dialysis, the predicted change in body water is in most studies larger than the observed weight loss as a result of a too large increase in impedance (33–36).

**CONCLUSIONS**

In the severely obese state several body-composition characteristics that affect the validity of the interpretation of impedance measurements may be different. An increased relative amount of TBW and a relative increase in extracellular water will result in an underprediction of percentage body fat when prediction equations developed in normal-weight subjects are applied to obese subjects. A different body build (mainly in those with severe abdominal obesity) will result in an overestimation of percentage body fat. The overall effect is probably an overestimation of FFM, and thus an underestimation of percentage body fat. Therefore, predicted percentage body fat from impedance measurements in obese subjects from both cross-sectional and longitudinal (eg, weight loss) studies must be interpreted with care. Individual changes < 1–2 kg TBW or
2–3 kg FFM cannot be reliably detected, regardless of possible violations in assumptions.

REFERENCES