Body composition in 5–18-y-old obese children and adolescents before and after weight reduction as assessed by deuterium dilution and bioelectrical impedance analysis

Martin Wabisch, Ulrike Braun, Eberhard Heinze, Rainer Muche, Hermann Mayer, Walter Teller, and Christoph Fusch

ABSTRACT The aim of the present study was to develop an equation for the prediction of total body water (TBW) from bioelectrical impedance analysis (BIA) in obese children and adolescents before and after weight reduction. In 146 obese subjects with a mean age of 12.7 ± 3.0 y (5.5–17.8 y), TBW was measured by using deuterium dilution as well as the resistance index (RI; height/2/resistance) using BIA before and after weight loss. Initially, the RI correlated well with measured TBW ($r^2 = 0.92$, $P < 0.001$). A multiple-regression analysis using forward stepwise selection of the variables RI, sex, age, weight, height, and waist-hip ratio revealed that the equation $\text{TBW} = 0.35 \times \text{RI} + 0.27 \times \text{age} + 0.14 \times \text{weight} - 0.12$ predicts most accurately individual values of TBW before weight loss (adjusted $r^2 = 0.96$, SEE = 1.9 L) with a mean error of predicted TBW of 1.40 ± 1.38 L. This equation was validated in 1000 random samples (bootstrap-sampling method), giving a mean $r^2$ of 0.95. During the weight-reduction program, which included an energy-restricted diet and an extensive exercise program, the patients lost 7.7 ± 3.2 kg, leading to a small decrease in TBW of 0.4 ± 1.5 L. When the developed prediction equation was applied to the data after weight loss, an $r^2$ value of 0.94 between measured and calculated TBW and a mean error of 2.18 ± 1.89 L was obtained. Validation of the equation in 1000 random samples after weight loss again gave a mean $r^2$ value of 0.95. Individual changes in predicted TBW correlated only weakly with those of measured TBW ($r = 0.21$, $P < 0.05$). Thus, individual TBW values before and after weight loss can be predicted by BIA with acceptable accuracy by using the developed equation. However, prediction of small individual changes in TBW during weight loss is not possible by BIA. Am J Clin Nutr 1996;64: 1–6.

KEY WORDS Body composition, obesity, children, bioelectrical impedance analysis, children, weight reduction

INTRODUCTION

Obesity is a frequent nutritional disorder in children and adolescents and its prevalence is increasing (1). Obesity in childhood has a major effect on health status in adulthood (2, 3), mainly because of the metabolic disturbances induced by this condition. The appropriate approach to reduce the obesity-related health risk is to reduce body weight, and it has been shown that weight reduction in obese children leads to an improvement of the atherogenic risk-factor profile (4–6).

For the assessment of obesity and the treatment of obese children and adolescents there is a need for a fast and easy method to estimate body composition accurately and reliably. It should be possible to determine changes in lean body mass during weight reduction to develop appropriate weight-reduction programs during which lean body mass remains stable and fat mass is preferably reduced. Several studies have shown that anthropometric measurements like weight, height, or skinfold thicknesses are not applicable in assessing body composition and its changes during weight loss in obese children because of their low precision and accuracy (7–12). Other more sophisticated methods like underwater weighing, deuterium dilution, dual-photon absorptiometry, computed tomography, and neutron-activation analysis are invasive and expensive and cannot be used in an outpatient setting.

Studies in adults have shown that bioelectrical impedance analysis (BIA) is an easy, applicable method for estimating lean body mass (13) or total body water (TBW) (14, 15). It is evident from recent studies that the use of BIA in the assessment of body composition in children requires that specific prediction formulas be different from those established for adults (15–21). Such formulas have been developed for the prediction of lean body mass (15–19) and of TBW (19–21) in lean children. BIA could also be an easy, applicable method for the assessment of body composition in obese children, but until now it has been validated for obese children only in one study with a small number of subjects ($n = 19$) (22). In this study a considerable overestimation of TBW by BIA was found when a prediction formula developed in lean children was applied (22). Until now, no studies have investigated the applicability of BIA in the assessment of body composition during and after weight loss in obese children.

1 From the Departments of Pediatrics I and Clinical Documentation, University of Ulm, Germany; the Children’s Hospital Hochfried, Murnau, Germany; and the Division of Neonatology, University Women’s Hospital, Berne, Switzerland.

2 Address reprint requests to M Wabisch, Department of Pediatrics I, University of Ulm, Prittwitzstrasse 43, 89075 Ulm, Germany.

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Because BIA is potentially a fast and safe method for assessing body composition in obese children and changes during weight reduction, we performed the present study and tried 1) to develop an easily applicable prediction equation for the calculation of TBW from BIA in a large group of obese children and adolescents, and 2) to validate BIA in the measurement of TBW and its changes after weight reduction.

SUBJECTS AND METHODS

Subjects

One hundred forty-six obese, white children and adolescents (69 boys and 77 girls) with a mean (± SD) age of 12.7 ± 3.0 y (range: 5.5–17.8 y) were included in the study. The distribution of the subjects over the whole age range from childhood to adolescence was well-balanced and as follows (boys/girls): 5.5–8.0 y, 7/4; 8.1–10.0 y, 9/10; 10.1–12.0 y, 13/16; 12.1–14.0 y, 14/13; 14.1–16.0 y, 19/19; and 16.1–17.8 y, 7/15. The patients had a mean body mass index (BMI; in kg/m²) of 28.8 ± 4.9 (18.2–47.0). On the basis of age-related percentiles for BMI, all subjects were above the 90th percentile (23). The subjects were admitted to the Children’s Hospital Hochried to participate in a weight-reduction program. All subjects were otherwise healthy as assessed by clinical examination and routine laboratory tests. The clinical data of the subjects are given in Table 1. The study was in accordance with the ethical standards of the responsible local committee on human experimentation. Informed, written consent was obtained from the parents and, when appropriate, also from the subjects after the nature of the procedures had been fully explained.

Study protocol

During the 40-d treatment period, subjects received a mixed diet with a mean (± SD) energy content of 4321 ± 523 kJ/d. Protein, carbohydrate, and fat provided 26%, 56%, and 18% of energy, respectively. All subjects took part in a controlled exercise program lasting 1–2 h/d consisting mainly of swimming, ball games, and jogging. In the evening of days 1 and 38 of the weight-reduction program, subjects received their individual deuterium dose to measure TBW as described below. On the same days, 2–3 h before deuterium was given, anthropometric measurements and BIA were performed.

<table>
<thead>
<tr>
<th>TABLE 1</th>
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<tbody>
<tr>
<td>Clinical data for the 146 obese children and adolescents before and after weight loss</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Before</th>
<th>After</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (kg)</td>
<td>74.1 ± 22.3 (33.0–132.4)</td>
<td>66.5 ± 19.9 (29.6–117.3)</td>
</tr>
<tr>
<td>Height (m)</td>
<td>158.5 ± 15.7 (117.5–194.0)</td>
<td>—</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>28.8 ± 4.8 (18.2–47.0)</td>
<td>25.8 ± 4.3 (16.4–42.8)</td>
</tr>
<tr>
<td>Weight loss (%)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Waist-hip ratio</td>
<td>0.89 ± 0.07 (0.74–1.02)</td>
<td>0.86 ± 0.06 (0.70–0.99)</td>
</tr>
<tr>
<td>RI (cm²/l)</td>
<td>48.7 ± 15.3 (21.9–102.9)</td>
<td>47.4 ± 15.6 (20.5–96.8)</td>
</tr>
<tr>
<td>TBW (L)</td>
<td>31.2 ± 9.3 (14.5–61.2)</td>
<td>30.8 ± 9.4 (13.4–61.6)</td>
</tr>
<tr>
<td>TBW (% by wt)</td>
<td>42.5 ± 4.1 (33.0–55.1)</td>
<td>46.7 ± 4.7 (38.5–62.9)</td>
</tr>
<tr>
<td>FFM (kg)</td>
<td>42.6 ± 12.7 (19.8–83.6)</td>
<td>42.1 ± 12.8 (18.4–81.1)</td>
</tr>
<tr>
<td>FFM (% by wt)</td>
<td>58.1 ± 5.7 (45.0–75.2)</td>
<td>63.8 ± 6.4 (52.6–86.0)</td>
</tr>
<tr>
<td>FM (kg)</td>
<td>31.5 ± 11.5 (9.9–63.3)</td>
<td>24.3 ± 9.3 (7.9–48.5)</td>
</tr>
<tr>
<td>FM (% by wt)</td>
<td>41.9 ± 5.7 (24.7–55.0)</td>
<td>36.2 ± 6.4 (6.4–47.4)</td>
</tr>
</tbody>
</table>

1 ± SD; range in parentheses. RI, resistance index; TBW, total body water; FFM, fat-free mass; FM, fat mass.

Anthropometric measurements

Weight was measured to the nearest 0.1 kg in subjects wearing light underwear on a calibrated balance-beam scale and height was measured to the nearest 0.5 cm. Waist circumference was measured midway between the lower rib margin and the ilioc crest; hip circumference was measured at the point yielding the maximum circumference over the buttocks. The waist-hip ratio (WHR) was calculated to obtain an index for the pattern of body fat distribution.

Bioelectrical impedance analysis

BIA was performed with an AKERN BIA 101/S (RJL Systems, Detroit) at a frequency of 50 kHz with a constant current of 0.8 mA. With the subject in a supine position, four electrodes were placed as described previously (14). The outer electrodes were positioned on the skin of the right hand, overlying the third metacarpal bone and on the skin of the third metatarsal bone close to the third toe. The inner electrodes were attached to the right wrist (dorsal surface in between protruding portions of the ulnar and radial bone) and the ankle (on the level of protruding parts of the tibial and fibular bone). The resistance index (RI = h²/resistance) was used to analyze the data.

Measurement of total body water

After having emptied their bladders (a sample was used to determine the predose tracer enrichment), subjects drank 0.4 mL D₂O/kg body wt (99.8% D₂O; Cambridge Isotope Laboratory, Innerberg, Switzerland) at 2200 for the measurement of TBW. After an overnight fast (2200–0700), blood was taken from an antecubital vein and was centrifugated at 400 × g for 10 min at room temperature within 2 h to obtain serum for determination of deuterium enrichment. Samples were kept frozen at −30 °C in small plastic containers until analyzed.

Measurement of deuterium enrichment

Deuterium-enrichment samples (100 μL) were prepared by using vacuum distillation (24). Deuterium concentrations were measured by using a Fourier-transform infrared spectrometer (IFS 66; Bruker, Karlsruhe, Germany) as described previously (24–26). The interday CV for the measurement of deuterium concentrations was <0.8%. Formulas described previously
(24) were used to calculate TBW from the deuterium enrichment in serum after correction by a factor of 1.04 for isotope sequestration (27). Fat-free mass (FFM) and fat mass (FM) were calculated from measured TBW according to the following formulas: FFM = TBW/0.732 (28) and FM = body weight − FFM.

**Data analysis and statistical methods**

Data are presented as means ± SDs. Differences between paired observations were tested by using the t test for paired variables. To describe the relation between two sets of data we used linear-regression analysis. All statistical calculations were done by using the Statistical Analysis System software (version 6.08; SAS Institute Inc, Cary, NC). P values < 0.05 were considered to be significant.

The analysis for the development of an equation for the prediction of TBW was done by forward stepwise variable selection in the multiple-linear-regression model (29). Six variables were chosen for modeling: RI, age, weight, sex, WHR, and height. (Sex was coded as follows: 1 = male; 2 = female.) These variables were used because they are easy to determine and because earlier studies in adults suggested that their inclusion in the equations led to an improvement in the prediction of TBW from BIA (15, 18, 30, 31). The variable WHR was included as a further estimate of body shape. The inclusion criteria for the forward deletion method were set to P < 0.2 (29). The $r^2$ value of the resulting model was used as a measure of goodness of fit and the SEE was used as a measure of model variation.

To validate the developed formula, 1000 sets of bootstrap samples (32) for a sample size of 146 were randomly drawn from the original data set. This procedure represents a reliable model for validating prediction formulas (30). For each set of bootstrap samples, an $r^2$ value between measured and predicted values of TBW was calculated. The mean $r^2$ and the 95% CI of the mean $r^2$ are given. The bootstrap-sampling procedure was also used to validate the accuracy of the developed formula in predicting TBW after weight loss. The mean error of the calculated TBW values by the developed formula was determined as follows:

$$\text{Mean error} = \frac{1}{n} \sum (\text{TBW}_{D2O} - \text{TBW}_{BIA})^2$$  \hspace{1cm} (1)

where TBW$_{D2O}$ is measured TBW and TBW$_{BIA}$ is calculated TBW.

**TABLE 2**

<table>
<thead>
<tr>
<th>Regression coefficients</th>
<th>RI</th>
<th>Weight</th>
<th>Age</th>
<th>WHR</th>
<th>Intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>0.58$^*$</td>
<td></td>
<td></td>
<td></td>
<td>0.92</td>
</tr>
<tr>
<td>Step 2</td>
<td>0.36$^*$</td>
<td>0.17$^*$</td>
<td></td>
<td></td>
<td>0.95</td>
</tr>
<tr>
<td>Step 3</td>
<td>0.35$^*$</td>
<td>0.14$^*$</td>
<td>0.27$^*$</td>
<td></td>
<td>0.96</td>
</tr>
<tr>
<td>Step 4</td>
<td>0.35$^*$</td>
<td>0.14$^*$</td>
<td>0.32$^*$</td>
<td></td>
<td>3.08</td>
</tr>
</tbody>
</table>

$^*$ P < 0.001.

$^*$ P < 0.01.

Investigation of the accuracy of the developed formula in predicting TBW from BIA after weight loss

To investigate the applicability of the developed prediction formula for the sample population after weight loss, the predicted TBW values after weight loss were compared with the measured values of TBW after weight loss. In addition, the accuracy of the developed formula in predicting TBW after weight loss was also investigated by bootstrap sampling, as mentioned above.

**RESULTS**

Body composition before and after weight reduction measured by deuterium dilution

Clinical and body-composition data for the 146 subjects before and after weight reduction are presented in Table 1. The mean TBW of the subjects before weight reduction was 31.2 ± 9.3 L, representing 42.5 ± 4.1% of body weight. During weight reduction, which included an energy-restricted diet and increased physical activity, the patients lost 7.7 ± 3.2 kg and their estimated FM decreased from 31.5 ± 11.5 to 24.3 ± 9.3 kg (P < 0.01), representing a reduction in FM from 41.9 ± 5.7% to 36.2 ± 6.4% of body weight (P < 0.01). There was a small but significant decrease in TBW (31.2 ± 9.3 compared with 30.8 ± 9.4 L, P < 0.05) and estimated FFM (42.6 ± 12.7 compared with 42.1 ± 12.8 kg, P < 0.05).

**Development and validation of an equation to predict TBW from the resistance index**

The equation used to predict TBW from BIA was developed by using the data from our subjects obtained before weight loss. The RI correlated well with TBW ($r^2 = 0.92, P < 0.001$), leading to an acceptable estimate of TBW. Multiple-regression analysis with forward-stepwise variable selection revealed that weight and age entered as significant variables into the model led to an increase in the $r^2$ value of the model to 0.96 (Table 2). The variables WHR, sex, and height did not enter into the model. The best prediction of TBW was achieved with the following equation:

$$\text{TBW} = 0.35 \times \text{RI} + 0.27 \times \text{age} + 0.14$$

$$\times \text{weight} - 0.12$$ \hspace{1cm} (2)

The SEE was 1.9 L. With this equation TBW could be predicted in our subjects from BIA with a mean error of 1.40 ± 1.38 L, or 4.5 ± 4.4%. TBW values measured by deuterium dilution plotted against those calculated with this equation are shown in Figure 1. Validation of this formula by using the bootstrap-sampling method (30) gave a mean $r^2$ value of 0.946 ± 0.0002 (95% CI: 0.945, 0.947), indicating an acceptable validation of the developed formula.

**Prediction of TBW from BIA after weight loss with the developed equation**

Using the developed equation we calculated the TBW values of the subjects after they had completed the 38-d weight-reduction program. The correlation coefficient between calculated and measured values for TBW was 0.96 (P < 0.001), comparable with the correlation coefficient between measured...
and calculated TBW values obtained before weight reduction. Similar to measured TBW values, predicted values also decreased slightly after weight loss (30.7 ± 8.9 compared with 29.2 ± 8.7 L, P < 0.05). TBW after weight loss could be predicted with a mean error of 2.18 ± 1.89 L, or 7.07 ± 6.13%. Validation of the developed formula with bootstrap sampling gave a mean $r^2$ of 0.947 ± 0.0002 (95% CI: 0.946, 0.947), indicating again an acceptable validation of the developed formula. The correlation between the changes of measured and predicted TBW during weight loss was low ($r = 0.21, P < 0.05$), showing that an accurate prediction of TBW changes by BIA is not possible in an individual subject during weight loss when TBW decreases only slightly (0.4 ± 1.5 L).

**DISCUSSION**

In the present study an equation was developed to predict TBW from BIA in a well-balanced population of obese children and adolescents before and after weight loss. Besides the RI, this equation includes the easily measurable indexes weight and age and can therefore be used as a fast method to estimate body composition in obese patients within this age group. See $r^2$ values of the developed equation as measures of goodness of fit and of model variation were equal or better than those reported for prediction formulas developed in lean adults or children (14–21). The reliability of the developed equation in assessing body composition in obese children and adolescents is further emphasized by its good validation in random samples of the population, before and after weight loss, drawn by bootstrap sampling (30).

Few studies have been published that present equations for the prediction of TBW from BIA in lean children. When applying the previously published formula of Davies et al (20), established in 26 lean children and adolescents from 5.2 to 17.8 y of age, to our data from obese children and adolescents, we found that TBW was underestimated (Figure 2). This finding supports the results of a study by Battistini et al (22), which until now was the only study performed in obese children. These authors developed an equation in a group of 19 obese children and included an estimate of body surface as an independent variable in the equation. When applying the formula of Battistini et al to our data we found a significant overestimation of TBW (Figure 3). This equation is therefore not applicable to our population. There is no study reported in the literature that investigated the applicability of an equation for the prediction of TBW from BIA in obese children and adolescents before and after weight loss.

Weight loss of the subjects ($\bar{x} \pm$ SD: 7.7 ± 3.2 kg) was mainly due to a loss of FM, with only minor changes in lean body mass because TBW decreased by only 0.4 L. This result is of special interest because an almost unchanged lean body mass result in a relatively stable resting metabolic rate, which should improve the prognosis of the weight reduction achieved.

Although individual TBW values after weight loss could be predicted by BIA with an acceptable accuracy, it was not possible to estimate accurately individual changes in TBW by using BIA. One of the reasons for this finding could be that only minor changes in TBW occurred, leading to a significant influence of the mean error of each measurement, 1.4 L.

Previously published studies investigating the feasibility of BIA in predicting changes in body composition during weight loss of children and adolescents showed almost no changes in TBW when applying the equation of Battistini et al (22). In the present study, however, significant changes in TBW were observed when applying the equation of Davies et al (20) developed in lean children. The reason for this is that the formula of Davies et al includes the body mass index, which is related to changes in body composition during weight loss.

**FIGURE 1.** Relation between individual values of measured total body water (TBW) and TBW calculated from bioelectrical impedance analysis (BIA) with the developed equation before weight loss.

**FIGURE 2.** Relation between individual values of measured total body water (TBW) and TBW calculated from bioelectrical impedance analysis (BIA) with the equation of Davies et al (20) developed in lean children: $0.35 \times \text{resistance index} + 0.27 \times \text{age} + 0.14 \times \text{weight} - 0.12$.

**FIGURE 3.** Relation between individual values of measured total body water (TBW) and TBW calculated from bioelectrical impedance analysis (BIA) with the equation of Battistini et al (22) developed in obese children.
loss in adults gave conflicting results (31, 34–39). The reasons for the different findings are difficult to explain and were discussed recently by Van der Kooy (34). Differences in the diet and the duration of weight reduction and the resulting changes in water and glycogen stores may have accounted for differences in the correlation between changes in body resistance and TBW or lean body mass (34). It should also be stressed that estimates of body-composition changes as assessed by all indirect methods may differ from true changes, which cannot be assessed by in vivo methods. Until now, no study published with proper validation of prediction formulas to assess changes in body composition by BIA has been published.

One recent study in obese adults showed that BIA overestimated the decrease in lean body mass during weight loss (34), confirming the findings of our study. An explanation for this overestimation may be the fact that body resistance determined at 50 kHz is influenced by the ratio of extracellular to intracellular water stores (40) and BIA measures mainly extracellular water and only partly intracellular water stores. Obese individuals may have relatively increased extracellular water stores and during weight loss a shift in the ratio of extracellular to intracellular water may occur. The BIA data obtained at 50 kHz before and after weight loss may therefore be difficult to compare. Theoretically, this would result in an overestimation of lean body mass before weight loss and an overestimation of loss of lean body mass during weight loss as found in our present study and a previous study (34).

In conclusion, we suggest that the equation we developed for the calculation of TBW from BIA provides an accurate prediction of individual values of TBW in obese children and adolescents in the age range from 5 to 18 y, both before and after weight loss. Our study showed that the prediction of small changes in TBW by BIA during weight loss in this population is not possible.

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REFERENCES


