A Prediction Equation for Total Body Water from Bioelectrical Impedance in Japanese Children

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Abstract Total body water (TBW) measured by isotope dilution techniques can be used to assess body composition safely and accurately in children. Unfortunately, this method is not readily available for most research projects, particularly when working with large groups of people, because the equipment is complicated and highly specialized. Bioelectrical impedance (BI) method is a simple, quick, and inexpensive method for the assessment of total body water (TBW). In Japanese child population, however, a lack of prediction equations is a problem to determine TBW. The purpose of this study was to determine the prediction equation for TBW determination in Japanese children using the isotope dilution technique as the reference method. Seventy Japanese children (39 boys, 31 girls) with ages ranging between 3 and 6 years participated in this study. They were randomly divided into the validation group (26 boys, 20 girls) and cross-validation group (13 boys, 11 girls). In a forward stepwise regression analysis, 96% of the variability in TBW measured by deuterium oxide (D\(_2\)O) dilution could be predicted by the following equation:

\[
\text{TBW(kg)} = 0.149 \times \text{Resistance Index (Stature}^2/\text{Resistance, cm}^2/\Omega) + 0.244 \times \text{Weight(kg)} + 0.460 \times \text{Age(y)} + 0.501 \times \text{Sex (boy} = 1, \text{girl} = 0) + 1.628, \text{with a root mean square error (RMSE) of 0.440 kg in the validation group. This equation predicted TBW in the cross-validation group with } R^2 = 0.946 \text{ and a pure error (PE) = 0.400 kg TBW. Hence, this equation should be applicable for predicting TBW in Japanese children aged 3–6 y. J Physiol Anthropol Appl Human Sci 23 (2): 35–39, 2004 http://www.jstage.jst.go.jp/browse/jpa

Keywords: total body water, bioelectrical impedance, children, prediction equation, resistance index

Introduction

The measurement of body composition has become an important procedure in nutrition and health-oriented assessment. For example, the prevalence of obesity in industrialized countries continues to be a major health problem (Kuczmarski et al., 1994; Flegal et al., 1998). This phenomenon is associated with an increased risk for developing chronic diseases including coronary heart disease, hypertension, and diabetes. Moreover, obesity in childhood found to be correlated with adult obesity (Power et al., 1997; Kotani et al., 1997). As a result, there is a need to easily make an accurate assessment of the body composition in children.

The established reference methods used for body composition assessment are densitometry, whole-body counting, and dual-energy x-ray absorptiometry. However, these methods are all very expensive and require trained operators. Moreover, these methods are very difficult to perform on children.

The measurement of body water is used to predict the fat-free mass (FFM), based on the principle that FFM contains a relatively constant proportion of water (Schoeller, 1996). The volume of water in the body can be readily measured by the isotope dilution technique. This method can evaluate the total body water (TBW) safely and accurately in children. Unfortunately, this method is not readily available for most research projects, particularly when working with large groups of children, since the equipment is complicated and highly specialized.

Bioelectrical impedance (BI) method is a simple, quick, and inexpensive method for the assessment of TBW (Kushner et al., 1992). The theoretical relationship between BI and TBW was proposed by Hoffer et al. (1969) based on earlier work by Thomasset (1962; 1963). Subsequent regression analyses by several investigators have demonstrated that the impedance index or the resistance index (RI; S\(^2\)/R where S is stature, and R is resistance) yielded higher correlation coefficients than weight or height when used as predictor of TBW (Kushner et al., 1986; Lukaski et al., 1986; Komiya and Masuda, 1990; Kushner, 1992).

Most research on predicting TBW with BI has been performed on adults. Few equations to predict TBW have been developed specifically for children (Davies et al., 1988; Fjeld et al., 1990; Danford et al., 1992; Wells et al., 1999). In these equations, RI has been a strong predictor of TBW, but the accuracy of predicting TBW by BI was improved greatly by the inclusion of additional variables such as weight (Fjeld et
In conclusion, the relationship between BI and TBW is influenced by age, even within a narrow age range in children. This necessitates the use of age-specific equations in the BI method. Therefore, the purpose of this study was to determine a prediction equation for TBW in Japanese children using the isotope dilution technique as the reference method.

Methods

Subjects

Seventy Japanese children (39 boys and 31 girls) with ages ranging between 3 and 6 years in four kindergartens in different parts of the city of Fukuoka participated in this study. All subjects were of Japanese origin, and had no known pathologies or physical handicaps. The informed consent was obtained from a parent of each child before participation. The study was approved by the Committee on Human Research for the Medical Sciences at the Nakamura-Gakuen University.

The total group of subjects was randomly divided into a validation group (26 boys and 20 girls) and cross-validation group (13 boys and 11 girls); the groups were closely matched in age, height, and weight.

Measurement of total body water (TBW)

TBW was measured by the deuterium oxide (D_2O) dilution technique as previously described (Komiya et al., 1992; Ube and Komiya, 1999). After an overnight fast, each subject emptied his or her bladder, then received orally 1 g per kilogram of body weight of 99.75% D_2O (Wako Pure Chemical Industries, Ltd. Japan), diluted in a quantity of drinking water to a D_2O concentration of 20% or less. After 1 and 3 hours equilibration period, urine samples were collected and stored at −10°C until analyzed. Each urine sample was then placed in a distillation apparatus, and the D_2O concentration was determined using a Fourier transform infrared spectrometer (FT-IR 8300, Shimadzu Corporation, Kyoto, Japan). D_2O dilution space was calculated as D_2O dilution space = volume of D_2O administered/urine D_2O concentration. D_2O dilution space was converted to TBW by dividing by 1.04 (Schoeller et al., 1980).

Measurement reliability of urine D_2O concentration

Between-day reliability of urine D_2O concentration measurement was assessed for two different concentrations of D_2O samples. The coefficient of variation (CV) was 0.5% and 0.6% respectively, when the two samples were measured over a series of 10 days.

Anthropometric and BI measurement

Stature was measured to the nearest 0.1 cm and weight to the nearest 0.02 kg on a balance beam scale (AD-6205, A&D Co., Ltd., Saitama, Japan).

Whole-body BI was measured by a bioelectrical impedance generator (TP-95K, Toyo Physical, Fukuoka, Japan), with four surface electrodes placed on the right wrist and ankle as described elsewhere (Lukaski et al., 1986). The principle was based on the application of an electrical current of 50 kHz and 500 μA produced by a generator and applied to the skin using adhesive electrodes (Red Dot-2330, 3M Health Care, MN, USA) with the subject lying supine as described elsewhere (Houtkooper et al., 1996). The skin was cleaned with alcohol. Before each testing session, the calibration of the unit was checked using a 400-Ω precision resistor.

Statistical analysis

The statistical analysis program StatView, version J-5.0 was used for statistical analysis. The results were expressed as means±standard deviations. Sex and group differences in physical characteristics, TBW, and BI variables were examined by unpaired t-test. Differences with p values less than 0.05 were considered significant.

In the validation group, the analysis for the development of an equation for the prediction of TBW was done by forward stepwise regression analysis. We chose four independent variables for modeling: resistance index (RI), weight, age, and sex (boy=1 and girl=0), because the impedance is inversely proportional to stature^2, weight expresses body size and correlate with TBW, and the distribution of TBW is influenced by age and the sex (Houtkooper et al., 1996). The R^2 value of the resulting model and the root mean square error (RMSE) were used as measures of goodness of the fit of the equation.

The multiple regression equations developed from the validation group were cross-validated on the cross-validation group. The pure error (PE; square root of mean of squares of differences between observed and predicted values) was used to measure the performance of the prediction equation on cross-validation. Paired t-test was used to compare TBW obtained BI prediction equation with TBW measured by isotope dilution. For assessment of agreement between BI and D_2O results, the statistical graphic approach proposed by Bland and Altman (1986) was used.

Results

The means±standard deviations for age, body size, TBW, and BI variables of the subgroups, and sex and group differences are shown in Table 1. In all variables, there were no significance differences between the validation and cross-validation groups among the boy or girl subsets. Although the resistance was higher in girls than in boys, other variables did not show a sex difference.

The multiple regression equations were developed for the prediction of TBW in the validation group. Forward stepwise
regression analysis was repeated and the results are shown in Table 2. The $R^2$ increased from 0.829 to 0.960, and the RMSE decreased from 0.904 to 0.440 including independent variables. RI, weight, age, and sex explained 96% of the variation in TBW as measured by the D$_2$O dilution technique. From these results, the following prediction equation was obtained.

$$
\text{TBW (kg)} = 0.149 \times \text{RI (cm}^2/\text{W)} + 0.244 \times \text{weight (kg)} \\
+ 0.460 \times \text{age (y)} + 0.501 \\
\times \text{sex (boy = 1, girl = 0)} + 1.628
$$

This prediction equation also yielded the lowest RMSE of 0.440 kg TBW. The relationship between TBW measured by the D$_2$O dilution technique and that predicted from the prediction equation in the validation group is presented in Fig. 1. The regression line ($Y = 0.999X + 0.004$) was very close to the identity line.

This prediction equation was then applied to the other 24 children. The cross-validation resulted in a high $R^2$ (0.946) and low PE (0.400 kg), as summarized in Fig. 2. Table 3 presents the comparison of measured and predicted TBW in cross-validation group. There was no significant difference between the measured TBW and predicted TBW results was 0.11 kg. The limits of agreement (mean±2SD) showed that results derived prediction equation might be 0.91 kg higher or 0.69 kg lower than those from measured by D$_2$O.

### Discussion

We determined TBW using the D$_2$O dilution technique in seventy Japanese children. The TBW measurements of approximately 11.5 kg for the present study were slightly lower than that derived for the several previous studies of approximately 13.0 to 17.0 kg (Danford et al., 1992; Kushner et al., 1992).

### Table 1

Age and physical characteristics of subjects

<table>
<thead>
<tr>
<th></th>
<th>Boys (n=39)</th>
<th>Girls (n=31)</th>
<th>Total (n=70)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Validation (n=26)</td>
<td>Cross-validation (n=13)</td>
<td>P</td>
</tr>
<tr>
<td>Age, yr</td>
<td>4.9±0.9</td>
<td>4.8±0.9</td>
<td>n.s.</td>
</tr>
<tr>
<td>Stature, cm</td>
<td>108.5±6.9</td>
<td>109.4±7.1</td>
<td>n.s.</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>18.9±3.0</td>
<td>19.4±4.0</td>
<td>n.s.</td>
</tr>
<tr>
<td>BMI, kg/m$^2$</td>
<td>15.7±1.6</td>
<td>16.0±1.6</td>
<td>n.s.</td>
</tr>
<tr>
<td>TBW, kg</td>
<td>11.6±1.9</td>
<td>11.6±1.7</td>
<td>n.s.</td>
</tr>
<tr>
<td>Resistance, Ω</td>
<td>670±65</td>
<td>670±67</td>
<td>n.s.</td>
</tr>
<tr>
<td>RI, cm$^2$/Ω</td>
<td>17.9±3.5</td>
<td>18.1±3.0</td>
<td>n.s.</td>
</tr>
</tbody>
</table>

Values are mean±standard deviation

TBW; total body water, RI; resistance index (stature$^2$/resistance)

### Table 2

Forward stepwise regression analysis for prediction of total body water

<table>
<thead>
<tr>
<th>Model</th>
<th>Independent variables</th>
<th>Regression coefficients</th>
<th>$R^2$</th>
<th>p</th>
<th>RMSE (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RI</td>
<td>0.532</td>
<td>0.829</td>
<td>&lt;0.001</td>
<td>0.904</td>
</tr>
<tr>
<td></td>
<td>Intercept</td>
<td>2.172</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>RI</td>
<td>0.250</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weight</td>
<td>0.227</td>
<td>0.940</td>
<td>&lt;0.001</td>
<td>0.536</td>
</tr>
<tr>
<td></td>
<td>Intercept</td>
<td>2.739</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>RI</td>
<td>0.205</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weight</td>
<td>0.215</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Age</td>
<td>0.356</td>
<td>0.949</td>
<td>&lt;0.001</td>
<td>0.493</td>
</tr>
<tr>
<td></td>
<td>Intercept</td>
<td>1.987</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>RI</td>
<td>0.149</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weight</td>
<td>0.244</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Age</td>
<td>0.460</td>
<td>0.960</td>
<td>&lt;0.001</td>
<td>0.440</td>
</tr>
<tr>
<td></td>
<td>Sex</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Intercept</td>
<td>1.628</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

RMSE; root mean square error
Although these previous studies have also used the D\textsubscript{2}O dilution technique, the mean age of subjects in the previous studies was higher than that in the present study (7–8 years vs. 5 years). Therefore, the TBW per body weight (TBW/W) did not vary between previous studies and the present study. For example, Hewitt et al. (1993) have reported that the mean weight and TBW values were 27.0±4.1 kg and 17.0±1.8 kg respectively, for seventeen white boys, and 30.0±5.8 kg weight and 17.1±2.7 kg TBW for eleven white girls. The TBW/W calculated by these values are 0.63 for boys, and 0.57 for girls. The TBW/W in the present study was 0.61 for boys, and 0.57 for girls. It is noteworthy that the TBW/W did not vary between white children and Japanese children. This result is in accordance with the results of a recent published study of Bray et al. (2001), who showed no significant difference in the average TBW values between black and white boys and girls aged 10–12 y. The corroboration also confirmed that the measurements of TBW in the present study were reasonable.

A major purpose of the present study was to determine a prediction equation for TBW determination in Japanese children, since there is a lack of prediction equations for the determination of TBW in this population.

To date, many equations for predicting TBW using BI have been developed and reviewed (Kushner, 1992; Houtkooper et al., 1996). In these reviews, the RI was reported to be the best single predictor of TBW by many of validation studies involving adults and children. Typically, the accuracy of predicting TBW is improved when body weight is included as a predictor in the equation, and also when age and sex are included.

In the present study, the prediction accuracies (R\textsuperscript{2} and RMSE) for TBW from RI alone were less than the accuracies for both RI and weight combined. Including age and sex in the prediction equation also improved the accuracy. The prediction accuracy (R\textsuperscript{2}=0.960, RMSE=0.440 kg) obtained from stepwise regression analysis in the present study is comparable with that reported from several previous studies for predicting TBW in children (Davies et al., 1988; Fjeld et al., 1990; Danford et al., 1992; Wells et al., 1999).

Typically, the accuracy of an equation is reduced when it is applied to other samples. Therefore, it is necessary to cross-validate to confirm the general validity of the prediction equation. We cross-validated our prediction equation obtained in the validation group by application to a cross-validation group. In our results, the correlation between predicted TBW values from the prediction equation and TBW values measured by the D\textsubscript{2}O dilution technique was very high (R\textsuperscript{2}=0.946) with a PE value of 0.400 kg. The results of paired t-test showed that there was no significant difference between the predicted and measured value of TBW. Furthermore, Bland-Altman plot showed that the limits of agreement were very small between predicted and measured TBW. These results are comparable to those reported from several previous studies reviewed by Houtkooper et al. (1996).
The results of the present study have shown the measurement of bioelectrical impedance to be a reliable and valid predictor of TBW in Japanese children. In addition, the results of cross-validation indicate that the present prediction equation will be applicable to other Japanese children. However, the age range of subjects in the present study was relatively narrow. Therefore, more research in different age groups in the Japanese child population is needed to obtain information about the validity of bioelectrical impedance to assess TBW.

Reference


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