



PAPER

Foot-to-foot bioelectrical impedance analysis: a valuable tool for the measurement of body composition in children

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OBJECTIVE: To determine the accuracy of foot-to-foot bioelectrical impedance analysis (BIA) and anthropometric indices as measures of body composition in children.

DESIGN: Comparison of foot-to-foot BIA and anthropometry to dual-energy X-ray absorptiometry (DEXA)-derived body composition in a multi-ethnic group of children.

SUBJECTS: Eighty-two European, NZ Maori and Pacific Island children aged 4.9–10.9 y.

MEASUREMENTS: DEXA body composition, foot-to-foot bioelectrical impedance, height, weight, hip and waist measurements.

RESULTS: Using a BIA prediction equation derived from our study population we found a high correlation between DEXA and BIA in the estimation of fat-free mass (FFM), fat mass (FM) and percentage body fat (PBF) ($r = 0.98, 0.98$ and 0.94 , respectively). BIA-FFM underestimated DEXA-FFM by a mean of 0.75 kg, BIA-FM overestimated DEXA-FM by a mean of 1.02 kg and BIA-PBF overestimated DEXA-PBF by a mean of 2.53%. The correlation between six anthropometric indices (body mass index (BMI), ponderal index, Chinn's weight-for-height index, BMI standard deviation score, weight-for-length index and Cole's weight-for-height index) and DEXA were also examined. The correlation of these indices with PBF was remarkably similar ($r = 0.85–0.87$), more variable with FM ($r = 0.77–0.94$) and poor with FFM ($r = 0.41–0.75$).

CONCLUSIONS: BIA correlated better than anthropometric indices in the estimation of FFM, FM and PBF. Foot-to-foot BIA is an accurate technique in the measurement of body composition.

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Keywords: foot-to-foot bioelectrical impedance; anthropometry; body composition; children

Introduction

There are several situations in pediatrics where accurate and simple measurement of body composition is needed. One such example is the area of childhood obesity research, where a simple measure of adiposity is needed so that large-scale studies can further elucidate the relationship between body fat and disease. Research techniques for measuring body composition include dual-energy X-ray absorptiometry (DEXA), underwater weighting and isotope

dilution. However, these techniques are not suitable for community studies or routine clinical use. Most assessments of body composition or nutrition in children are based on anthropometric measures of weight, height or skinfold thickness (SFT). Most childhood obesity research has used body mass index (BMI), which is an inaccurate measure of adiposity, especially in more obese children.¹ There are a number of other indices which are based on weight, height and/or age which have also been reported for use in the nutritional assessment of children,^{2,3} however most of these have not been validated against reference methods of body composition.

Bioelectrical impedance analysis (BIA) offers additional body composition information to routine anthropometry. BIA is based on the theoretical relationship between the volume of a conductor and its impedance. When applied

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to the human body it assumes that the fat-free mass (FFM) contains virtually all the body's conducting electrolytes. The impedance value is combined with anthropometric data into a prediction equation to give body compartment measures. Conventional BIA has been shown to be accurate at predicting FFM and total body water in children.^{4–12} The few studies that have examined its ability to predict percentage body fat (PBF) found that BIA was superior to BMI and that BIA was similar to SFT performed by trained observers.^{4,5,13,14} BIA is painless, requires less training and is subject to less interobserver variation than SFT measurement.⁶ Conventional BIA requires careful placement of electrodes on the arm and leg. Foot-to-foot BIA is simpler and only requires that the subject stand on the pad electrodes, and measurement takes only one minute. Foot-to-foot BIA is comparable to conventional BIA in adults.¹⁵ It has not been validated in children, nor has any form of BIA been validated in New Zealand (NZ) Maori or Pacific Island children.

The purpose of the present study was to examine the ability of foot-to-foot BIA and anthropometry to predict FFM, fat mass (FM) and PBF in 5–10 y-old children. We included European, NZ Maori and Pacific Island children with a range of weights, including obese children. DEXA was used as the reference method of body composition measurement. We compared several different anthropometric indices, including BMI, ponderal index and weight for height index against body composition. We derived a foot-to-foot BIA prediction equation for the estimation of body composition in children.

Methods

Subjects

Children, aged 5–10, were recruited from Auckland schools or were the children of colleagues. Inclusion criteria were: (i) absence of significant chronic disease, recent hospitalization or specialist follow-up; (ii) freedom from drugs known to influence body composition or appetite, such as oral steroids, stimulants, growth hormone and cigarette smoking. Children were chosen to provide a range of BMIs within each ethnic group.

Methods

The parent-assigned ethnicity of each child was recorded and combined into four groups: European, NZ Maori, Pacific Island or Mixed (Maori and Pacific Island). The pubertal stage of the child was determined according to Tanner.¹⁶ Each child then had height, hip and waist girths measured to the nearest 1 mm and the mean of three repeated measurements recorded. Height was measured using a Harpenden stadiometer and waist and hip girth using a plastic measuring tape. All measurements were made by one of two observers (GG, VT). Weight and foot-to-foot bioelectrical impedance were measured using a Tanita/Stellar Innovations Inc. Bioelectrical Impedance Analyzer (Tokyo, Japan) and the

mean of two measurements recorded. Children were measured wearing preweighed hospital gowns and bare weight determined to the nearest 100 g. Anthropometric indices for each child were derived using the equations shown in Table 1.

Three-compartment body composition (soft tissue mass, fat mass and bone mineral content) was determined by Lunar DPX-L DEXA (Madison, WI, USA) using manufacturer's software. When compared to chemically determined mass the accuracy of Lunar DEXA-determined assessments of body composition are high, with correlations of >0.99 for lean tissue mass and bone mass and 0.95 for fat mass.³⁷ For analysis the soft tissue mass and BMC were combined to give the fat-free mass (FFM), and percentage body fat (PBF) calculated by the equation $PBF = FM/(FM+FFM) \times 100$. Children were scanned wearing light clothing, lying supine and had all metal, bone or shell (eg buttons and zips) accessories removed.

We derived a prediction equation to determine BIA-FFM in our population. BIA-FM was calculated by subtracting the BIA-FFM from the weight and BIA-PBF calculated by dividing BIA-FM by the weight, and expressed as a percentage.

Written informed consent was obtained from the parent prior to beginning testing and the study design was approved by the regional ethics committee.

Statistical analysis

Stepwise linear regression was used to investigate the prediction of BIA-FFM from the impedance, anthropometric and demographic variables. Pearson's correlation was used to test the relationship between anthropometric indices and DEXA-derived body composition measures. The Bland–Altman method¹⁷ was used to test the agreement between DEXA and BIA measures of FFM, FM and PBF. The Bland–Altman method calculates the mean difference, or bias, between the two methods and upper and lower limits of agreement, which is the difference ± 2 s.d. If the level of agreement,

Table 1 Anthropometric indices; the equations used to calculate various anthropometric indices used in the nutritional assessment of children, are shown

Index	Reference	Calculation
BMI		wt/ht ²
Rohrer's ponderal index	2	wt/ht ³
Chinn's weight for height (WFH) index	34	(wt–9)/(ht) ^{3.7}
Weight for length index (WLI)	35	WFA/HFA \times 100
Cole's WFH index	36	WFA/(HFA) ²
BMI standard deviation score (SDS)	21	(BMI–mean BMI for age)/s.d.
Waist-to-hip ratio		waist/hip

wt = weight (kg) and ht = height (m).

WFA (weight for age) = weight/50th percentile expected weight for age.

HFA (height for age) = height/50th percentile expected height for age.

s.d. = standard deviation.

determined by the upper and lower limits of agreement, is clinically acceptable then the two methods can be used interchangeably. Intraclass correlations were calculated to investigate the reliability of two consecutive BIA measurements of weight and impedance. The Bland–Altman was also used to test the agreement between DEXA-derived body weight and measured body weight.

Results

The study sample consisted of 85 healthy children. Three children were excluded from analysis, two were unable to lie still for the DEXA scan and one was scanned on the incorrect settings. The physical characteristics of the remaining 82 children are shown in Table 2. Their ages ranged from 4.9 to 10.9 y. Seventy children were prepubertal and 12 had Tanner stage II pubertal development. Twenty-seven (33%) of the children had a BMI greater than the 95th percentile for age, a commonly used definition of obesity.^{18,19} We derived a BIA-FFM prediction equation based on the impedance index ($ZI = \text{height}^2/\text{impedance}$). The ZI explained most of the variation of the DEXA-FFM with an r^2 value of 0.94. Using a stepwise regression we found that the addition of height, weight and sex to the equation improved the r^2 to 0.97. Pubertal stage, age, ethnicity and the interactions between the various factors did not meet the significance level required for inclusion in the model. The prediction equation derived from our population is:

$$\text{BIA-FFM} = 0.31 \times \text{ZI} + 0.17 \times \text{height} + 0.11 \times \text{weight} \\ + 0.942 \times \text{sex} - 14.96$$

(where sex = 1 for females and 2 for males).

Agreement between the DEXA-FFM and BIA-FFM was tested using the method described by Bland and Altman,¹⁷

Table 2 Demographic and physical characteristics of the study population

Sex: male/female	36/46
Pubertal stage: Tanner I/Tanner II	70/12
Ethnicity:	
European	48
Maori	16
Pacific Island	13
Mixed	5
Age (y)	8.1 ± 1.5 (4.9, 10.9)
Weight (kg)	33.8 ± 13.3 (17.1, 71.2)
Height (cm)	131.6 ± 12.1 (109.4, 158.4)
BMI (kg/m ²)	18.9 ± 4.3 (12.3, 33.1)
BMI-SDS	0.86 ± 1.7 (-1.9, 5.4)
Waist/hip ratio	0.85 ± 0.05 (0.72, 1.00)
Impedance (Ω)	554 ± 65 (397, 738)
DEXA-FFM (kg)	23.2 ± 6.2 (13.1, 40.9)
DEXA-FM (kg)	10.3 ± 7.4 (2.6, 34.1)
DEXA-PBF	28.1 ± 9.8 (10.9, 49.2)

Values for sex, ethnicity and pubertal stage are number of subjects in each group. Other values are presented as means ± s.d. with the range in parentheses.

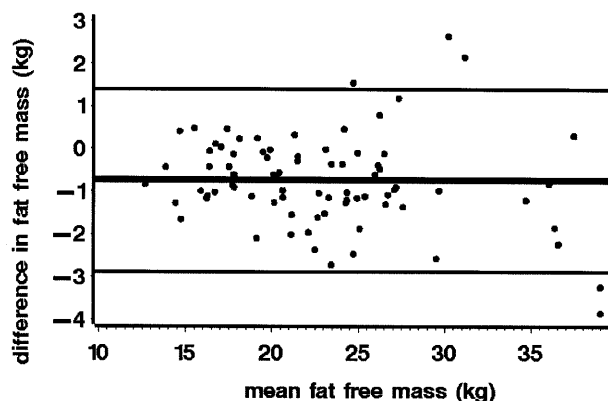


Figure 1 Comparison of DEXA-derived estimation of fat-free mass with the difference between DEXA- and BIA-derived estimates of fat-free mass. Expressed as mean ± 2 s.d.

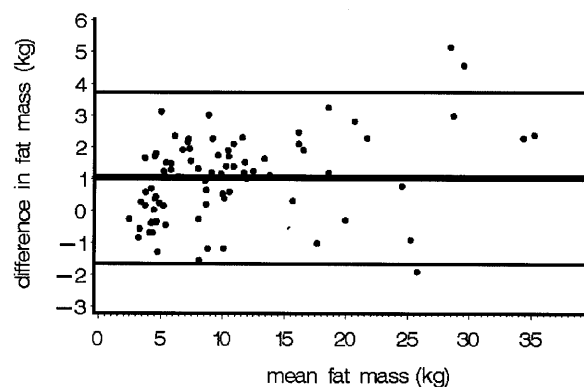


Figure 2 Comparison of DEXA-derived estimation of fat mass with the difference between DEXA- and BIA-derived estimates of fat mass. Expressed as mean ± 2 s.d.

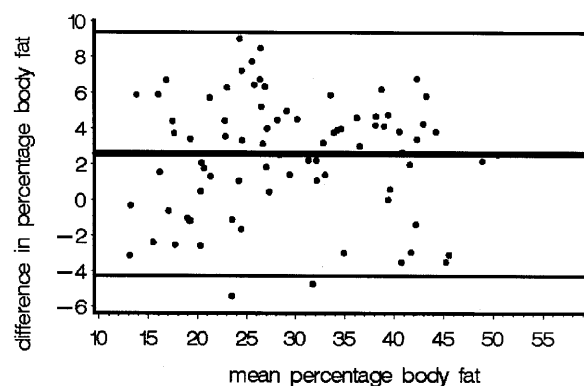


Figure 3 Comparison of DEXA-derived estimation of percentage body fat with the difference between DEXA- and BIA-derived estimates of percentage body fat. Expressed as mean ± 2 s.d.

Table 3 Correlation coefficients (*r*) between anthropometric indices and DEXA-derived body composition

	DEXA-FFM	DEXA-FM	DEXA-PBF
BIA—our equation	0.98	0.98	0.94
BMI	0.75	0.94	0.87
Ponderal index	0.41	0.77	0.87
Chinn's WFH	0.53	0.81	0.87
BMI-SDS	0.54	0.80	0.86
WLI	0.69	0.89	0.85
Cole's WFH	0.61	0.87	0.87
Waist-to-hip ratio	0.02	0.08	0.03

see Figures 1–3. BIA-FFM underestimated the DEXA-FFM by a mean of 0.75 kg. The limits of agreement were -2.89 and 1.38 kg, ie the BIA-FFM value could range from 2.89 kg below to 1.38 kg above the DEXA-FFM value. We then calculated the BIA-FM and BIA-PBF. The BIA-FM overestimated the DEXA-FM by a mean of 1.02 kg (limits of agreement -1.66 and 3.71 kg). The BIA-PBF overestimated the DEXA-PBF by a mean of 2.53% (limits of agreement -4.29 and 9.36%).

Pearson's correlation was used to test the relationship between various anthropometric indices and body composition. The correlation coefficient (*r*) for each index and FFM, FM and PBF are shown in Table 3.

The intraclass correlation for two repeated BIA measurements on the same day showed reliability for impedance measures of 0.995 and for weight measures of 0.999 . The Bland–Altman was used to compare the BIA weight and electronic scales weight (available in 60 children) and showed a mean difference of -0.015 kg (limits of agreement -0.18 and 0.15 kg). The Bland–Altman was also used to compare the DEXA-derived weight (the sum of the FM and FFM) and the BIA measured weight and showed a mean difference of -0.27 kg (limits of agreement -1.66 and 1.12), ie the DEXA-derived weight underestimated the true weight by a mean of 0.27 kg.

Discussion

We have demonstrated that foot-to-foot BIA is a useful tool for measuring body composition in children. The r^2 between BIA-FFM and DEXA-FFM in this series of children was better than that reported in adults ($r^2 = 0.97$ and $r^2 = 0.79$,¹⁵ respectively) and similar to that reported in children by traditional BIA methods ($r^2 = 0.95$ – 0.98).^{4–9,11,12} Foot-to-foot BIA offers the advantage of simplicity and speed, taking less than 1 min to perform. Using this equipment the reproducibility of measurements of impedance and weight is excellent.

BIA is a useful tool but its accuracy depends on the use of an appropriate prediction equation. It has been recommended that an equation be validated on each different BIA analyser and for each population in which it is to be used.^{4,12,20} When considering validation of BIA it is important to understand the statistical methods used. Many authors only report the correlation between BIA and the

reference method and this can be misleading as it does not test the equivalence of the results given by the different methods. It is necessary to test the level of agreement between BIA and DEXA and we therefore used the method described by Bland and Altman.¹⁷ Authors have recommended that researchers aim to cross-validate one of the already published prediction equations. There are many published equations for use with conventional BIA but this is the first prediction equation for foot-to-foot BIA in children. Foot-to-foot BIA measures the impedance of the lower half of the body, compared to conventional arm to-leg BIA, which measures the impedance of the arm, trunk and leg, and it would therefore not be appropriate to use an equation derived for whole-body impedance. The foot-to-foot prediction equation needs further validation to determine its applicability to other populations.

We aimed to validate BIA in our three main ethnic groups; European, NZ Maori and Pacific Island. Using stepwise regression, ethnicity, pubertal stage and age were not included our prediction equation. It is possible that the inclusion of weight and height in the ethnic groups were small, limiting the ability to detect small differences, however in our model the ZI explained most of the variation in BIA. There was no statistical evidence to indicate that there were interactions with ethnicity and therefore the same prediction equation can be used for European, Maori and Pacific Island children. The same equation can also be used for children aged 5–10 y who are Tanner stage I or II. It is possible that a different prediction equation would be needed for later pubertal stages as the relationship of intracellular and extracellular water is known to differ between children and adults.¹² Our equation has also been derived in a population of children with a wide range of body compositions, including very obese children with PBF up to 49% .

The BIA has quite wide limits of agreement with DEXA measurements of body composition and therefore the two methods are not interchangeable. Limits of agreement were poorest for PBF values where the BIA could vary from the DEXA by -4.29 to $+9.36\%$. This illustrates that BIA is not a gold standard for body composition measurement in an individual. The imprecision is due to the highly derived nature of the values determined by BIA prediction equations. However, the mean differences between BIA and DEXA are not as large (-0.75 kg for FFM, $+1.02$ kg for FM, $+2.53\%$ for PBF) and BIA is therefore an acceptable tool for measuring large groups of children.

Anthropometric indices, based on weight, are the most commonly used tool for assessing childhood nutrition and body composition. These indices determine the appropriateness of a child's weight by taking into consideration the child's height and/or age. An ideal index of relative weight would be independent of both height and age. The BMI (W/H^2) and ponderal index (W/H^3) both make a correction for height but have been criticised because they are still not independent of height.³ Neither these indices, nor Chinn's WFH index are corrected for the child's age. Age and ethni-

city-specific normal values for BMI are available,²¹ but similar tables do not exist for the ponderal index or Chinn's index, which limits their usefulness. Weight for length index (WLI), Cole's WHI and BMI-SDS make corrections for the child's height and age. Indeed WLI has been shown to be independent of both age and height.³ We determined how these various indices performed against a reference measure of body composition to further assess their validity. In past studies BMI has shown variable correlation with reference measures of body composition (DEXA, underwater weighing or isotope dilution) explaining between 60 and 87% of the variance in FM and between 38 and 87% of the variance in PBF.^{1,4,5,13,14,22,23} Ponderal index has been reported to explain 68% of the variance in PBF.²³ None of the other indices we have used have been compared to reference measures of body composition in children. In our study we tested indices of weight adjusted for height, ie BMI, ponderal index and Chinn's index, and those adjusted for both height and age, ie BMI-SDS, WLI and Cole's WFH index, against DEXA-derived body composition. All of the indices were remarkably similar in their correlation with PBF ($r=0.85-0.87$). There was more variation in their correlation with FM ($r=0.77-0.94$), and BMI was the most highly correlated with FM ($r=0.94$). These indices were poorly correlated with FFM ($r=0.41-0.75$) and this throws doubt on their role in the assessment of undernutrition and chronic disease in children. Waist-to-hip ratio showed no useful association with body composition and did not predict the FM or PBF. We did not test its ability to predict regional body fat distribution.

Foot-to-foot BIA was superior to anthropometric indices in its correlation with FFM, FM and PBF. BIA prediction equations use both impedance and anthropometric data. The clearest benefit of this over anthropometric data alone is in the prediction of FFM. This is not surprising as FFM contains virtually all the body's conducting electrolytes and therefore determines the impedance. Overall, BIA provided the single most useful tool for the measurement of body composition in children in our community.

In this study we used DEXA as our reference method of measuring body composition in children. Criticism has been made of the use of DEXA in this role.²⁴ However, there is no true gold standard for the measurement of body composition in children. Other methods such as hydrodensitometry, isotope dilution and total body potassium estimation are also flawed. They rely on assumptions about the hydration and composition of the FFM, which vary during childhood, and may also vary with obesity and between ethnicities.²⁵⁻²⁷ Hydrodensitometry is also difficult to perform in children, with 13-17% unable or unwilling to do the necessary manoeuvres.^{28,29} Imaging techniques such as computerized tomography (CT) and magnetic resonance imaging (MRI) provide accurate measurement of body composition, but CT is not appropriate because of its high radiation exposure and the use of MRI is limited by cost and availability. DEXA is simple and safe, with only minimal radiation dose ($<1 \mu\text{S}$). It

requires the child to lie still for up to 20 min and is well tolerated. Only two children (3%) were unable to lie still for the required time. DEXA has been validated in the pediatric weight range by direct carcass analysis of pigs.^{30,31} The principles behind DEXA are less reliant on assumptions about biological consistency than other methods. It measures three body compartments and therefore overcomes some of the assumptions made by the other two compartment methods about the composition of FFM. One way of determining the accuracy of DEXA is to compare the weight derived from the sum of the three DEXA body compartments with the weight measured by electronic scales and, in our series, DEXA underestimated the measured weight by 0.27 kg. Other authors have found DEXA to underestimate measured weight by 0.19-0.83 kg.^{24,32,33}

In summary, BIA provides a reliable and accurate tool for the measurement of body composition (FFM, FM and PBF) in populations of children. The foot-to-foot method of BIA has made measurement simple, quick and portable and it is therefore an ideal tool for population-based studies. We have derived a BIA prediction equation for use in our population and have found that the same prediction equation can be used to assess children from the three different ethnicities and who are aged 5-10.9 y. Commonly used anthropometric indices showed good correlation with the FM and PBF, but weaker correlation with FFM in the children in our study. Given that age- and sex-specific reference values are available for BMI it appears the most useful of the anthropometric indices we tested.

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