Validation of foot-to-foot bioelectrical impedance analysis with dual-energy X-ray absorptiometry in the assessment of body composition in young children: the EarlyBird cohort

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(Received 27 April 2006 – Revised 4 August 2006 – Accepted 30 August 2006)

Foot-to-foot bioelectrical impedance analysis (BIA) is simple and non-invasive, making it particularly suitable for use in children. There is insufficient evidence of the validity of foot-to-foot BIA compared with dual-energy X-ray absorptiometry (DEXA) as the criterion method in healthy young children. Our objective was to assess the validity of foot-to-foot BIA against DEXA in a large cohort of healthy young children. Body composition was measured by foot-to-foot BIA and DEXA in 203 children (mean age 8.9 (sd 0.3) years). Bland–Altman and simple linear regression analyses were used to determine agreement between methods. BIA overestimated fat-free mass by a mean of 2.4 % in boys and 5.7 % in girls, while fat mass was underestimated by 6.5 % in boys and 10.3 % in girls. The percentage fat recorded by BIA was, accordingly, also lower than by DEXA (boys 4.8 %; girls 12.8 %). In boys, however, there were correlations between the size of the difference between methods and the size of the measure under consideration such that in smaller boys fat-free mass was underestimated (r 0.74 for fat mass; r 0.69 for percentage fat; both P<0.001) with the reverse in bigger boys. Mean differences between techniques were greater in the girls than in the boys but in boys only, the direction of the differences was dependent upon the size of the child. Therefore, BIA may be useful for large-scale studies but is not interchangeable with DEXA and should be interpreted with caution in individuals.

Validation: Bioelectrical impedance analysis: Dual-energy X-ray absorptiometry: Children: Body composition

Globally, both under- and over-nutrition are major health problems in children (de Onis & Blossner, 2003). The prime medical importance of obesity lies with the insulin resistance it causes, which in turn depends on the fat mass relative to lean mass, and its location. Body weight and BMI do not reflect either body composition or fat distribution and for research purposes several methods of determining body composition and fat distribution have been devised, some more accessible than others (Ellis, 2000; Heymsfield et al. 2005). Such methods include hydrodensitometry (underwater weighing), isotope dilution (³H-labelled water, ²H-labelled water, or ¹⁸O), bioelectrical impedance analysis (BIA), whole-body counting (for example, total body K), dual-energy X-ray absorptiometry (DEXA), magnetic resonance imaging, and computed tomography (Ellis, 2000; Heymsfield et al. 2005). There is, however, no ‘gold standard’ technique, as direct analysis of body composition can only be carried out by chemical analysis of cadavers.

Failing direct analysis, magnetic resonance imaging and computed tomography are considered as criterion methods since they provide visual images of adipose tissue and can reliably distinguish between intra-abdominal and subcutaneous fat. These methods have also been directly validated against cadaver analyses of body composition (Ross & Janssen, 2005). DEXA is more suitable for use in children because of the minimal radiation exposure and relative comfort. DEXA has been shown to be accurate and precise (Lohman & Chen, 2005), and its adoption as a criterion method is justified by successful validation against multi-compartment models (Sopher et al. 2004; Lohman & Chen, 2005) and against chemical analysis of animal models (Pintauro et al. 1996).

DEXA, however, is of limited availability, relatively expensive and time consuming. BIA is quick, cheap, and easy to use, making it particularly suitable for large-scale studies in children. BIA measures the body’s impedance and the technique is based on the differing electrical conductivities (water content) of various components of the body (Kyle et al. 2004a,b).

The traditional technique of BIA uses gel electrodes attached to wrist and ankle, and is in widespread use, but pressure-contact electrode systems (similar to bathroom scales) have since been introduced, which are more practical and convenient. Validation studies have been carried out in adults and adolescents (Jebb et al. 2000), and several studies that assess the foot-to-foot system include young children (Jartti et al. 2000; Tyrrell et al. 2001; Sung et al. 2001; Goss et al. 2003; Parker et al. 2003; Pietrobelli et al. 2004). Previous studies, however, have been

Abbreviations: BIA, bioelectrical impedance analysis; DEXA, dual-energy X-ray absorptiometry.
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limited by a wide age range and/or small sample size (Sung et al.
1991; Parker et al. 2003; Pietrobelli et al. 2004), or lack of criterion method for comparison (Jartti et al. 2000; Goss et al.
2003). There is still therefore a lack of information of the validity of foot-to-foot BIA compared with DEXA in young children (Tyrrell et al. 2001), and some doubt remains over its adequacy (Lukaski & Siders, 2003). The aim of the present study was to assess the validity of the foot-to-foot BIA in a large cohort of healthy young children using DEXA as the standard.

Methods

EarlyBird is a non-intervention prospective cohort study of 307 healthy school entrants (170 boys, 137 girls; mean age 4·9 years) in the city of Plymouth (UK). The study’s rationale, recruitment procedures and protocol have been detailed previously (Voss et al. 2003). Exclusion criteria were diabetes, pathological states likely to affect growth or body composition, moderate or severe physical disability, and long-term use of oral steroids assessed using a detailed medical history questionnaire (updated every 6 months). Measurements were made at recruitment and annually thereafter of height, weight, BMI, sum of skinfold thickness at five sites on the left-hand side of the body (triceps, biceps, subcapular, supra-iliac and umbilical) by skinfold callipers (Holtain Ltd, Crosswell, Dyfed, UK), and waist circumference by metal circumference measure (Chasmors Ltd, London, UK). All skinfolds and circumferences are the mean of two repeats. Height was recorded to the nearest 1 mm (Leicester Height Measure; Child Growth Foundation, London, UK) and the mean of three measures taken, weight to the nearest 100 g by the BIA (integral to the system). Reproducibility of the anthropometric measurements is expressed by the CV. Within-observer CV for height was 0·15 and 0·13 % for observers 1 and 2 respectively. Within-observer CV for waist circumference was 0·9 % for both observers. For the sum of five skinfold thickness sites, the CV was 3·7 and 4·0 % for observers 1 and 2 respectively. Foot-to-foot BIA was performed using the Tanita Body Composition Analyser TBF-300M (Tanita UK Ltd, West Drayton, Middlesex, UK), which is a stand-on system and the manufacturer’s in-built equation was used for calculation of body composition. The within- and between-day CV for this system have previously been reported as 0·9 % (SD 0·5) and 2·1 % (SD 1·0) respectively in adults (Nunez et al. 1997). Whole-body DEXA scans were performed with the Lunar Prodigy Advance fan-beam densitometer and analysed using EnCore 2004 software (version 8.10.02; GE Lunar Corporation, Madison, WI, USA). CV for total body composition by this system have recently been reported to range from 0·18 to 1·97 % among paediatric subjects (Margulies et al. 2005). All measurements were performed between 08.30 and 09.00 hours after a minimum 10 to 11 h fast with the subjects in bare feet and light clothing. The data reported here relate to 203 children (106 boys; ninety-seven girls) who completed both measurements at mean age 8·9 (SD 0·3) years. All were Caucasian except for five who were of mixed race.

Statistical analysis

Skinfold data were not normally distributed and were therefore subject to log transformation before analysis. The mean and CI therefore required anti-logging. Anthropometric and body composition comparisons between sexes were made using ANOVA. Differences between methods were explored using paired $t$ tests and Bland–Altman analyses (Bland & Altman, 1986). Pearson’s correlation coefficient was used to determine the association between techniques and between the size of the measurements and the difference between them. Where there was no relationship between the size of the measurements and the difference between them, the limits of agreement were calculated by $d \pm 1·96sd_{	ext{diff}}$ (where $d$ is mean difference and $sd_{	ext{diff}}$ is standard deviation of the differences). However, where there was such a relationship, the above calculation would give limits of agreement that are too far apart, failing to account for the relationship between the difference and the mean. In this situation, the limits of agreement were determined using a regression-based approach, where the difference between methods ($D$) was regressed on the average of the two methods ($A$), giving $D = b_0 + b_1A$. When there is no relationship between the residuals of this regression and $A$ (as was the case here), the limits of agreement can be calculated as $D \pm 1·96sd_{	ext{resid}}$ (where $sd_{	ext{resid}}$ is the standard deviation of the residuals from the regression).

Statistical significance was set at the 0·05 level and all statistical analyses were carried out using SPSS for Windows (version 11.5.1; SPSS Inc., Chicago, IL, USA).

Results

Anthropometry

The waist circumferences of the girls and boys were similar, but the mean sum of skinfold thicknesses of the girls was almost 30 % higher (Table 1), indicating higher adiposity (percentage body fat) of the girls.

Densitometry and bioelectrical impedance

The correlations between DEXA and BIA measures of fat-free mass, fat mass, and percentage fat were high in both boys and girls. For fat-free mass the correlations between DEXA and BIA were $r$ 0·93 and 0·95 for boys and girls respectively. For fat mass the correlations between DEXA and BIA were $r$ 0·97 and 0·99 for boys and girls respectively. For percentage fat the correlations between DEXA and BIA were $r$ 0·92 and 0·95 for boys and girls respectively. Table 2 compares body composition of the children using DEXA and BIA. The absolute fat-free mass recorded by BIA was greater than by DEXA both in boys (2·4%; $P<0·001$) and in girls (5·7%; $P<0·001$), and the absolute fat mass lower (boys 6·5%; $P=0·004$; girls 10·3%; $P<0·001$). The percentage fat recorded by BIA was, accordingly, also lower than by DEXA (boys 5·0%; $P<0·01$; girls 13·7%; $P<0·001$).

Systemisation of differences between bioelectrical impedance analysis and dual-energy X-ray absorptiometry

Table 2 also shows how the differences between BIA and DEXA were greater in the girls for all three variables measured (fat-free mass, fat mass and percentage fat (all $P<0·001$)). However, Table 3 examines each difference as a function of the variable measured in boys and girls separately and it can be seen that, for the boys, but not for the girls,
the differences between BIA and DEXA were dependent upon
the size of the variable in each case. Transcribed onto Bland–
Altman plots, Fig. 1 shows how in boys, but not in girls, BIA
tended systematically to underestimate fat-free mass at low
levels of FFM, but to overestimate it progressively at higher
levels. Also in boys, but not in girls, BIA overestimated fat
mass (Fig. 2) and percentage fat (Fig. 3) at low levels of fat
and to underestimate both at higher levels. In girls, BIA
tended to overestimate throughout the range of fat free mass
(Fig. 1), while fat mass (Fig. 2) and percentage fat (Fig. 3)
tended to be underestimated throughout the range.

Thus, in the boys but not the girls, the direction of the
differences was dependent upon size of the child. The influ-
ence of size on the accuracy of measurement was sometimes
substantial: r^2 0.74 (P < 0.001) in the case of fat mass
(boys), r 0.69 (P < 0.001) for percentage fat (boys) and
r^2 0.57 (P < 0.001) for fat-free mass (boys).

Discussion
We have examined the validity in young children of body
composition estimates by foot-to-foot BIA, using DEXA as
the criterion measure. We sought to establish whether the
differences between BIA and DEXA measures of body
composition were sex-sensitive and whether they were influ-
enced by body size. The data suggest that estimates of body
composition in 9-year-old children by foot-to-foot BIA are
not interchangeable with those from DEXA, owing to the
influence of one of the variables it is designed to measure –
body fat. As a result, foot-to-foot BIA tended to underestimate
percentage fat in fatter boys and to overestimate percentage fat
in leaner boys. In girls, the mean differences in body compo-
sition between the two techniques were larger than in the boys,
but they were not influenced by the size of the measures. It is
also important to note that although the mean differences may
small, of more relevance are the 95 % limits of agreement,
which are a more accurate reflection of the validity of the
measure in an individual.

Previous validation studies in adults and children have var-
iously found foot-to-foot BIA to underestimate, or to overesti-
mate, body fat in relation to DEXA (Tyrrell et al. 2001; Sung
Different populations, life or developmental stage, ethnicity
and use of different systems may explain some of these discrep-
ancies. Comparison with other studies is difficult, as few
have attempted to validate foot-to-foot BIA directly against
DEXA in young children. Those that made measurements
using both BIA and DEXA have a wider age range than the
present study, and age-related differences in fat patterning
may be critical to the performance of body composition
equations. Pietrobelli et al. (2004), for example, measured
forty subjects aged between 6 and 64 years, comparing both
segmental and foot-to-foot BIA with DEXA and found no
between-method bias. However, although the mean difference

| Table 1. Anthropometric characteristics of the EarlyBird cohort at 9 years |
|----------------------------------|--|--|--|---|
| Boys (n = 106) | Girls (n = 97) |
| Mean | 95 % CI | Mean | 95 % CI |
| Age (years) | 8.90 | 8.84, 8.96 | 8.85 | 8.79, 8.91 |
| Height (cm) | 134.4 | 133.2, 135.6 | 133.2 | 132.0, 134.4 |
| Weight (kg) | 30.9 | 29.6, 32.2 | 32.1 | 30.5, 33.7 |
| Impedance (Ω) | 615.5 | 603.0, 628.1 | 650.8 | 638.2, 663.5 |
| BMI (kg/m²) | 17.2 | 16.7, 17.7 | 18.0 | 17.4, 18.7 |
| Waist (cm) | 58.9 | 57.7, 60.1 | 59.3 | 57.8, 60.8 |
| Sum of skinfolds* (mm) | 51.2 | 47.3, 55.3 | 64.6 | 60.3, 69.2 |

* Back-transformed mean and CI of logged data.

| Table 2. Body composition by dual-energy X-ray absorptiometry (DEXA) and foot-to-foot bioelectrical impedance analysis (BIA) in the EarlyBird cohort at 9 years |
|----------------------------------|--|--|--|---|
| Boys (n = 106) | Girls (n = 97) |
| Mean | 95 % CI | Mean | 95 % CI |
| Weight (kg) | 30.7 | 29.4, 31.9 | 31.7 | 30.1, 33.3 |
| BIA | 30.9 | 29.6, 32.2 | 32.1 | 30.5, 33.7 |
| Fat-free mass (kg) | 24.5 | 23.9, 25.0 | 23.0 | 22.4, 23.6 |
| BIA | 25.1 | 24.4, 25.9 | 24.3 | 23.6, 24.9 |
| Fat mass (kg) | 5.2 | 5.4, 7.0 | 8.7 | 7.6, 9.8 |
| BIA | 5.8 | 5.2, 6.4 | 7.8 | 6.7, 8.8 |
| Fat (%) | 18.6 | 16.9, 20.4 | 25.7 | 24.0, 27.4 |
| BIA | 17.7 | 16.5, 18.9 | 22.4 | 20.7, 24.1 |
between methods was not statistically significant (probably due to small sample size), the correlation between techniques was lower ($r = 0.82$) than in the present study. In addition, neither the Bland–Altman plots nor 95% limits of agreement were presented, which are important to determine validity at an individual level.

Our population incorporated a large number of healthy, pre-pubertal children of uniform age. Others have included, or studied exclusively, adolescents (Sung et al. 2001; Lazzer et al. 2003; Parker et al. 2003; Pietrobelli et al. 2004). Consistent with the present findings, Lazzer et al. (2003) found that foot-to-foot impedance underestimated fat mass and percentage body fat when compared with DEXA in twenty male and thirty-three female overweight adolescents. Tyrell et al. (2001) compared body composition measured by foot-to-foot BIA and anthropometry to that measured by

### Table 3. Differences and limits of agreement at the 25th, 50th and 75th centiles of fat-free mass, fat mass and percentage fat measured by dual-energy X-ray absorptiometry (DEXA) and foot-to-foot (BIA) in children at 9 years (Mean differences and 95% limits of agreement)

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<tr>
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<th>Boys</th>
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<th>Girls</th>
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<td>Percentile</td>
<td>Mean difference</td>
<td>95% limits of agreement</td>
<td>Mean difference</td>
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<td>-2.42, 2.47</td>
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<td></td>
<td>50th</td>
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<td>-2.99, 1.90</td>
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<td></td>
<td>75th</td>
<td>-1.18</td>
<td>-3.63, 1.26</td>
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<tr>
<td>Fat mass (kg)</td>
<td>25th</td>
<td>-0.39</td>
<td>-2.24, 1.46</td>
<td>0.94*</td>
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<td>50th</td>
<td>0.04</td>
<td>-1.81, 1.89</td>
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<td></td>
<td>75th</td>
<td>0.78</td>
<td>-1.07, 2.63</td>
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<tr>
<td>Percentage fat</td>
<td>25th</td>
<td>-1.38</td>
<td>-7.24, 4.48</td>
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<tr>
<td></td>
<td>50th</td>
<td>0.32</td>
<td>-5.54, 6.18</td>
<td>3.27*</td>
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<td>75th</td>
<td>2.47</td>
<td>-3.39, 8.33</td>
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* Mean difference only is given where there was no relationship between difference and mean (girls).

![Fig. 1. Bland–Altman plot relating to fat-free mass (FFM) measured by dual-energy X-ray absorptiometry (DEXA) and foot-to-foot bioelectrical impedance analysis (BIA) in healthy 9-year-old boys (a) and girls (b). Lines are the regression slope $\pm 1.96$ so of residuals.](http://www.cambridge.org/core/)

![Fig. 2. Bland–Altman plot relating to fat mass (FM) measured by dual-energy X-ray absorptiometry (DEXA) and foot-to-foot bioelectrical impedance analysis (BIA) in healthy 9-year-old boys (a) and girls (b). Lines are the regression slope $\pm 1.96$ so of residuals.](http://www.cambridge.org/core/)
Differences in DEXA and BIA measurements in young children. (a) Bland–Altman plot relating to percentage fat measured by dual-energy X-ray absorptiometry (DEXA) and foot-to-foot bioelectrical impedance analysis (BIA) in healthy 9-year-old boys (a) and girls (b). Lines are the regression slope ±1.96 SD of residuals.

DEXA in a multi-ethnic group of eighty-two children aged between 4·9 and 10·9 years. However, in place of the manufacturer’s equation used in the present study, they customised an equation based on their study population. In contrast to the findings of the present study, BIA overestimated rather than underestimated percentage fat (Tyrrell et al. 2001). The use of different BIA equations and different DEXA technologies may explain the discrepancies. The present study used a fan-beam system, the aforementioned a pencil-beam machine. Also, in contrast to the present study, Sung et al. (2001) also found that BIA overestimated fat mass and percentage fat in seventeen obese and thirty-two non-obese Hong Kong Chinese children aged between 7 and 18 years, but with narrower limits of agreement and smaller differences between methods than the present study. The different ethnicity and age range of the populations under study, as well as the different DEXA technologies used, may again at least partly explain this discrepancy.

There are some shortcomings to the present study. Although widely considered a gold-standard technique in the measurement of body composition, DEXA may not be universally acceptable. The present study used a fan-beam DEXA system, whose measures have been shown to differ from the older pencil-beam systems (Tothill & Hannan, 2000; Genton et al. 2002; Lohman & Chen, 2005). Much previous validation of DEXA was carried out using pencil-beam machines (Lohman & Chen, 2005), and validation of the fan-beam DEXA is ongoing (Chauhan et al. 2003; Norcross & Van, 2004; Lohman & Chen, 2005; Genton et al. 2006). An assumption of DEXA is that anteroposterior thickness of the subject does not affect the measurement but there is some evidence to suggest that this is not the case, particularly at thicknesses greater than 25 cm (Lohman & Chen, 2005). However, there may be less of an effect for subject thicknesses less than 20 cm (Lohman & Chen, 2005) and use of the appropriate scan mode should help overcome this problem. Furthermore, other so-called ‘gold-standard’ techniques are not suitable for use in young children, and are not themselves free of limitations. The strengths of the present study lie with the large sample size and largely homogeneous population with respect to ethnicity and age.

In conclusion, in young children (boys and girls aged about 9 years), the two techniques are not directly interchangeable for individual children owing to the wide limits of agreement. However, the foot-to-foot BIA device may be suitable for use in large-scale epidemiological studies due to the high correlation and small mean differences between techniques, and its simplicity and its speed may offer particular advantage to children. Further validation studies would increase the utility of foot-to-foot BIA in individual children.

Acknowledgements

The present study was funded by Diabetes UK, Child Growth Foundation, Eli Lilly and London Law Trust. The paper was jointly written by all the authors and all took part in the study design. T. J. W. had the original idea and is guarantor for the EarlyBird study and L. D. V. is study coordinator. J. H. was responsible for the data analysis and writing the manuscript. B. S. M. provided statistical consultation for data analysis. A. N. J. was responsible for collection of the data. We also thank Sharan Griffin who was responsible for DEXA scanning. There are no conflicts of interest.

References


