

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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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 ($r = 0.57$; $P < 0.001$) while fat mass and percentage fat were overestimated ($r = 0.74$ 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 (Jarti *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.* 2001; 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, subscapular, 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 8.10.027; GE Lunar Corporation, Madison, WI, USA). CV for total body analysis 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 $\bar{d} \pm 1.96SD_{\text{diff}}$ (where \bar{d} is mean difference and SD_{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 $\hat{D} = b_0 + b_1A$. 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 $\hat{D} \pm 1.96SD_{\text{resid}}$ (where SD_{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 r 0.95 for boys and girls respectively. For fat mass the correlations between DEXA and BIA were r 0.97 and r 0.99 for boys and girls respectively. For percentage fat the correlations between DEXA and BIA were r 0.92 and r 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,

Table 1. Anthropometric characteristics of the EarlyBird cohort at 9 years (Mean values and 95% CI)

	Boys (n 106)		Girls (n 97)		P
	Mean	95% CI	Mean	95% CI	
Age (years)	8.90	8.84, 8.96	8.85	8.79, 8.91	0.25
Height (cm)	134.4	133.2, 135.6	133.2	132.0, 134.4	0.16
Weight (kg)	30.9	29.6, 32.2	32.1	30.5, 33.7	0.27
Impedance (Ω)	615.5	603.0, 628.1	650.8	638.2, 663.5	<0.001
BMI (kg/m^2)	17.2	16.7, 17.7	18.0	17.4, 18.7	0.03
Waist (cm)	58.9	57.7, 60.1	59.3	57.8, 60.8	0.67
Sum of skinfolds* (mm)	51.2	47.3, 55.3	64.6	60.3, 69.2	<0.001

*Back-transformed mean and CI of logged data.

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 influence of size on the accuracy of measurement was sometimes substantial: $r = 0.74$ ($P < 0.001$) in the case of fat mass (boys), $r = 0.69$ ($P < 0.001$) for percentage fat (boys) and $r = 0.57$ ($P < 0.001$) 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 influenced 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 composition 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 be 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 variously found foot-to-foot BIA to underestimate, or to overestimate, body fat in relation to DEXA (Tyrrell *et al.* 2001; Sung *et al.* 2001; Lazzar *et al.* 2003; Lukaski & Siders, 2003). Different populations, life or developmental stage, ethnicity and use of different systems may explain some of these discrepancies. 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. Pirotbelli *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 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 (Mean values and 95% CI)

	Boys (n 106)		Girls (n 97)		P value for sex difference
	Mean	95% CI	Mean	95% CI	
Weight (kg)					
DEXA	30.7	29.4, 31.9	31.7	30.1, 33.3	0.31
BIA	30.9	29.6, 32.2	32.1	30.5, 33.7	0.27
Fat-free mass (kg)					
DEXA	24.5	23.9, 25.0	23.0	22.4, 23.6	0.001
BIA	25.1	24.4, 25.9	24.3	23.6, 24.9	0.10
Fat mass (kg)					
DEXA	6.2	5.4, 7.0	8.7	7.6, 9.8	<0.001
BIA	5.8	5.2, 6.4	7.8	6.7, 8.8	0.001
Fat (%)					
DEXA	18.6	16.9, 20.4	25.7	24.0, 27.4	<0.001
BIA	17.7	16.5, 18.9	22.4	20.7, 24.1	<0.001

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)

	Percentile	Boys		Girls	
		Mean difference	95% limits of agreement	Mean difference	95% limits of agreement
Fat-free mass (kg)	25th	0.03	-2.42, 2.47	-1.29*	-3.23, 0.65
	50th	-0.54	-2.99, 1.90		
	75th	-1.18	-3.63, 1.26		
Fat mass (kg)	25th	-0.39	-2.24, 1.46	0.94*	-0.76, 2.63
	50th	0.04	-1.81, 1.89		
	75th	0.78	-1.07, 2.63		
Percentage fat	25th	-1.38	-7.24, 4.48	3.27*	-2.05, 8.59
	50th	0.32	-5.54, 6.18		
	75th	2.47	-3.39, 8.33		

* Mean difference only is given where there was no relationship between difference and mean (girls).

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; Lazzar

et al. 2003; Parker *et al.* 2003; Pietrobelli *et al.* 2004). Consistent with the present findings, Lazzar *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

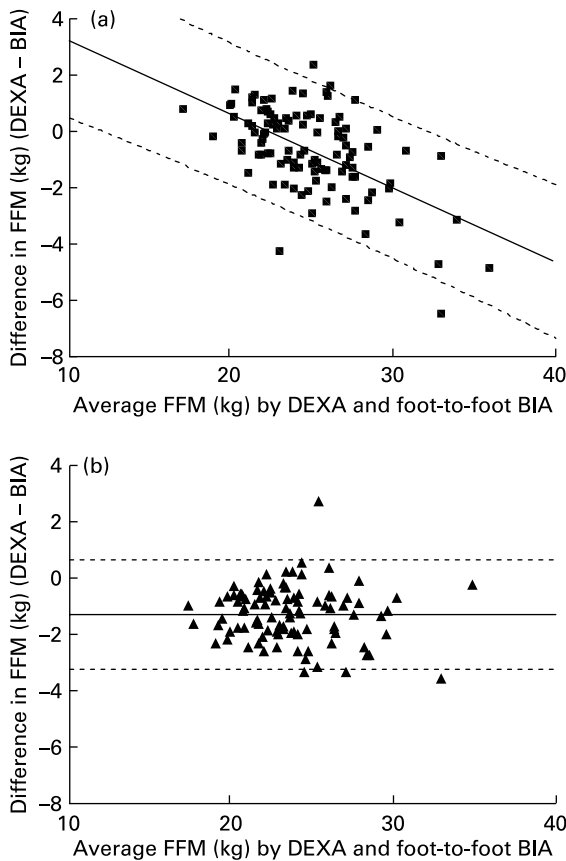


Fig. 1. Bland–Altman plot relating to fat-free mass (FFM) measured by dual-energy X-ray absorptiometry (DEXA) and foot-to-foot bioelectrical impedance analysis (BIA) in healthy 9-year-old boys (a) and girls (b). Lines are the regression slope \pm 1.96 SD of residuals.

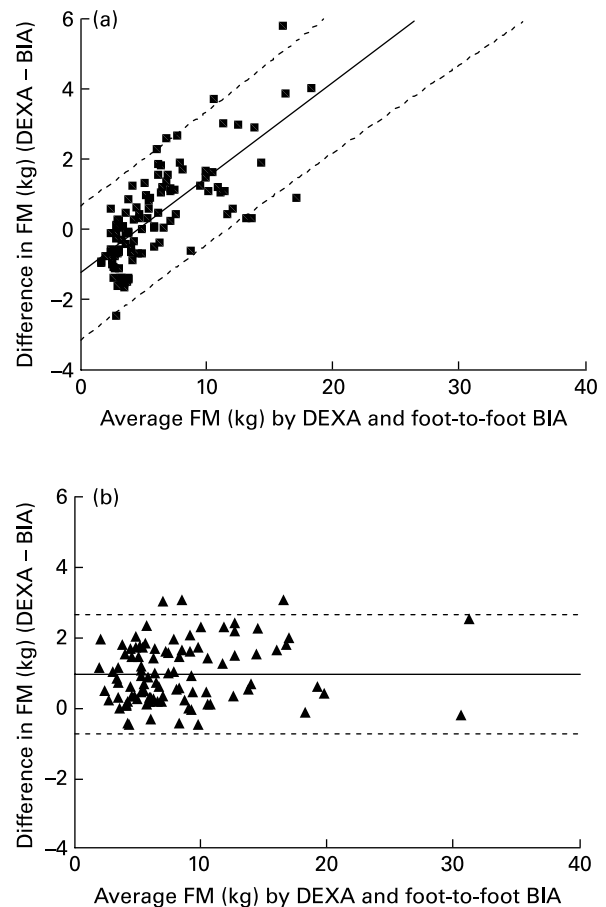


Fig. 2. Bland–Altman plot relating to fat mass (FM) measured by dual-energy X-ray absorptiometry (DEXA) and foot-to-foot bioelectrical impedance analysis (BIA) in healthy 9-year-old boys (a) and girls (b). Lines are the regression slope \pm 1.96 SD of residuals.

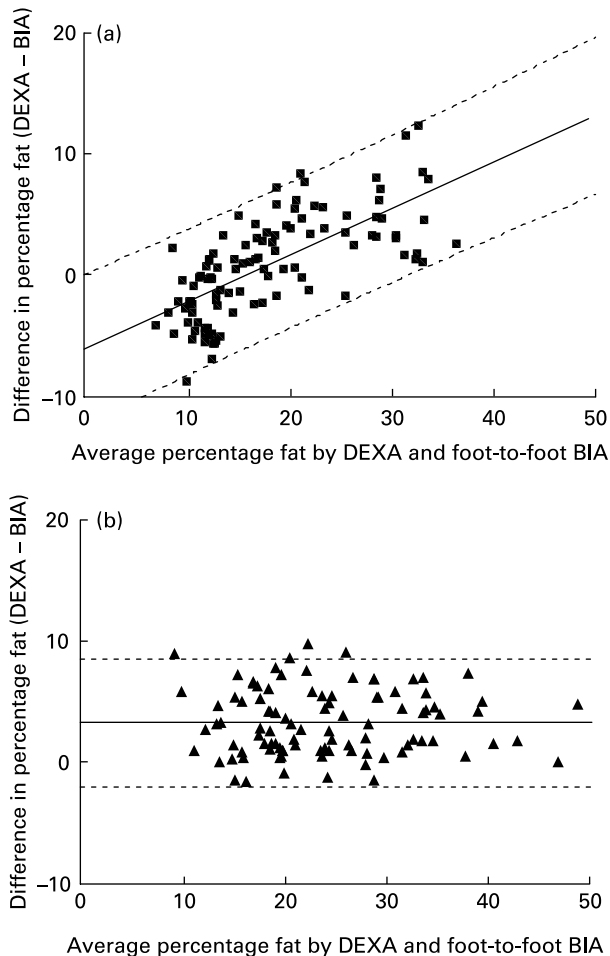


Fig. 3. Bland-Altman plot relating to percentage fat measured by dual-energy X-ray absorptiometry (DEXA) and foot-to-foot bioelectrical impedance analysis (BIA) in healthy 9-year-old boys (a) and girls (b). Lines are the regression slope ± 1.96 SD of residuals.

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.

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References

- Bland JM & Altman DG (1986) Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* **i**, 307-310.
- Chauhan S, Koo WW, Hammami M & Hockman EM (2003) Fan beam dual energy X-ray absorptiometry body composition measurements in piglets. *J Am Coll Nutr* **22**, 408-414.
- de Onis M & Blossner M (2003) The World Health Organization global database on child growth and malnutrition: methodology and applications. *Int J Epidemiol* **32**, 518-526.
- Ellis KJ (2000) Human body composition: *in vivo* methods. *Physiol Rev* **80**, 649-680.
- Genton L, Hans D, Kyle UG & Pichard C (2002) Dual-energy X-ray absorptiometry and body composition: differences between devices and comparison with reference methods. *Nutrition* **18**, 66-70.
- Genton L, Karsegard VL, Zawadzynski S, Kyle UG, Pichard C, Golay A & Hans DB (2006) Comparison of body weight and composition measured by two different dual energy X-ray absorptiometry devices and three acquisition modes in obese women. *Clin Nutr* **25**, 428-437.

- Goss F, Robertson R, Williams A, Sward K, Abt K, Ladewig M, Timmer J & Dixon C (2003) A comparison of skinfolds and leg-to-leg bioelectrical impedance for the assessment of body composition in children. *Dyn Med* **2**, 5.
- Heymsfield SB, Lohman TG, Wang Z & Going SB (2005) *Human Body Composition*. Champaign, IL: Human Kinetics Ltd.
- Jartti L, Hakanen M, Paakkunainen U, Raittinen P & Ronnema T (2000) Comparison of hand-to-leg and leg-to-leg bioelectric impedance devices in the assessment of body adiposity in prepubertal children. The STRIP study. Special Turku coronary Risk factor Intervention Project. *Acta Paediatr* **89**, 781–786.
- Jebb SA, Cole TJ, Doman D, Murgatroyd PR & Prentice AM (2000) Evaluation of the novel Tanita body-fat analyser to measure body composition by comparison with a four-compartment model. *Br J Nutr* **83**, 115–122.
- Kyle UG, Bosaeus I, De Lorenzo AD, *et al.* (2004a) Bioelectrical impedance analysis – part I: review of principles and methods. *Clin Nutr* **23**, 1226–1243.
- Kyle UG, Bosaeus I, De Lorenzo AD, *et al.* (2004b) Bioelectrical impedance analysis – part II: utilization in clinical practice. *Clin Nutr* **23**, 1430–1453.
- Lazzer S, Boirie Y, Meyer M & Vermorel M (2003) Evaluation of two foot-to-foot bioelectrical impedance analysers to assess body composition in overweight and obese adolescents. *Br J Nutr* **90**, 987–992.
- Lohman TG & Chen Z (2005) Dual energy X-ray absorptiometry. In *Human Body Composition*, pp. 63–77 [SB Heymsfield, TG Lohman, Z Wang and SB Going, editors]. Champaign, IL: Human Kinetics Ltd.
- Lukaski HC & Siders WA (2003) Validity and accuracy of regional bioelectrical impedance devices to determine whole-body fatness. *Nutrition* **19**, 851–857.
- Margulies L, Horlick M, Thornton JC, Wang J, Ioannidou E & Heymsfield SB (2005) Reproducibility of pediatric whole body bone and body composition measures by dual-energy X-ray absorptiometry using the GE Lunar Prodigy. *J Clin Densitom* **8**, 298–304.
- Norcross J & Van L (2004) Validation of fan beam dual energy x ray absorptiometry for body composition assessment in adults aged 18–45 years. *Br J Sports Med* **38**, 472–476.
- Nunez C, Gallagher D, Visser M, Pi-Sunyer FX, Wang Z & Heymsfield SB (1997) Bioimpedance analysis: evaluation of leg-to-leg system based on pressure contact footpad electrodes. *Med Sci Sports Exerc* **29**, 524–531.
- Parker L, Reilly JJ, Slater C, Wells JC & Pitsiladis Y (2003) Validity of six field and laboratory methods for measurement of body composition in boys. *Obes Res* **11**, 852–858.
- Pietrobelli A, Rubiano F, St-Onge MP & Heymsfield SB (2004) New bioimpedance analysis system: improved phenotyping with whole-body analysis. *Eur J Clin Nutr* **58**, 1479–1484.
- Pintauro SJ, Nagy TR, Duthie CM & Goran MI (1996) Cross-calibration of fat and lean measurements by dual-energy X-ray absorptiometry to pig carcass analysis in the pediatric body weight range. *Am J Clin Nutr* **63**, 293–298.
- Ross R & Janssen I (2005) Computed tomography and magnetic resonance imaging. In *Human Body Composition*, pp. 89–108 [SB Heymsfield, TG Lohman, Z Wang and SB Going, editors]. Champaign, IL: Human Kinetics Europe Ltd.
- Sopher AB, Thornton JC, Wang J, Pierson RN Jr, Heymsfield SB & Horlick M (2004) Measurement of percentage of body fat in 411 children and adolescents: a comparison of dual-energy X-ray absorptiometry with a four-compartment model. *Pediatrics* **113**, 1285–1290.
- Sung RY, Lau P, Yu CW, Lam PK & Nelson EA (2001) Measurement of body fat using leg to leg bioimpedance. *Arch Dis Child* **85**, 263–267.
- Tothill P & Hannan WJ (2000) Comparisons between Hologic QDR 1000W, QDR 4500A, and Lunar Expert dual-energy X-ray absorptiometry scanners used for measuring total body bone and soft tissue. *Ann N Y Acad Sci* **904**, 63–71.
- Tyrrell VJ, Richards G, Hofman P, Gillies GF, Robinson E & Cutfield WS (2001) Foot-to-foot bioelectrical impedance analysis: a valuable tool for the measurement of body composition in children. *Int J Obes Relat Metab Disord* **25**, 273–278.
- Voss LD, Kirkby J, Metcalf BS, Jeffery AN, O’Riordan C, Murphy MJ & Wilkin TJ (2003) Preventable factors in childhood that lead to insulin resistance, diabetes mellitus and the metabolic syndrome: the EarlyBird diabetes study 1. *J Pediatr Endocrinol Metab* **16**, 1211–1224.