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Evaluation of bioelectrical impedance analysis in measuring body fat in 6-to-12-year-old boys compared with air displacement plethysmography

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Abstract

Air displacement plethysmography (ADP) has been considered as the 'standard' method to determine body fat in children due to superior validity and reliability compared with bioelectrical impedance analysis (BIA). However, ADP and BIA are often used interchangeably despite few studies comparing measures of percentage body fat by ADP (%FM_{ADP}) with BIA (%FM_{BIA}) in children with and without obesity. The objective of this study was to measure concurrent validity and reliability of %FM_{ADP} and %FM_{BIA} in 6-to-12-year-old boys with and without obesity. Seventy-one boys (twenty-five with obesity) underwent body composition assessment. Ten boys participated in intra-day reliability analysis. %FM_{ADP} was estimated by Bodpod using sex- and age-specific equations of body density. %FM_{BIA} was estimated by a multi-frequency, hand-to-foot device using child-specific equations based on impedance. Validity was assessed by *t* tests, correlation coefficients and limits of agreement (LoA); and reliability by technical error of measurement (TEM) and intraclass correlation coefficients (ICC). Compared with %FM_{ADP}, %FM_{BIA} was significantly underestimated in the cohort (–3·4 ± 5·6 %; effect size = 0·42) and in both boys with obesity (–5·2 ± 5·5 %; ES = 0·90) and without obesity (–2·4 ± 5·5 %; ES = 0·52). A strong, significant positive correlation was found between %FM_{ADP} and %FM_{BIA} (r = 0·80). Across the cohort, LoA were 22·3 %, and no proportional bias was detected. For reliability, TEM were 0·65 % and 0·55 %, and ICC were 0·93 and 0·95 for %FM_{BIA} and %FM_{ADP}, respectively. Whilst both %FM_{ADP} and %FM_{BIA} are highly reliable methods, considerable differences indicated that the devices cannot be used interchangeably in boys age 6-to-12 years.

Key words: **Body composition: Obesity: Paediatric: Concurrent validity: Reliability**

Childhood obesity is associated with significant morbidity and mortality[1,2]. Co-morbidities associated with childhood obesity affect almost every body system, including, but not limited to, endocrine, cardiovascular, cardiometabolic and musculoskeletal systems[3]. Worldwide prevalence of childhood overweight and obesity increased from 12·8 % in 2000 to 14·2 % in 2013 and is expected to reach 15·8 % in 2025[4]. Growth trajectories for childhood obesity into adulthood indicate that 57·3 % of today's children and 75 % of children currently with obesity will be obese at the age of 35 years[5]. Monitoring and tracking of obesity in childhood appears critical to determine when preventative or management interventions should be taken.

Obesity is defined as excess fat accumulation that may impair health[6]. However, obesity is commonly measured by BMI which, in children, is transformed into BMI z-scores to define age- and sex-specific cut-offs for overweight and obesity[7]. BMI is useful for tracking changes in obesity prevalence in populations; however, the relationship between BMI and adiposity is not consistent across populations and assumes a linear increase in body mass and fat mass through childhood[8,9]. Measures of adiposity (i.e. fat mass relative to body mass (%FM)), rather than weight relative to height, provide accurate assessment of obesity status and may provide better indication of the effectiveness of weight loss programmes[10,11].

Reference methods of measuring adiposity include computerised tomography, magnetic resonance imaging, dual-energy X-ray absorptiometry, isotope dilution and combinations of methods to construct three (3C) and four (4C) compartment models. Reference methods are accurate assessments of %FM (compared with 'gold-standard' cadaver analysis)[12], because measurements of hydration status and mineral content are included in the %FM calculation[9]. However, in comparison with two compartment (2C) models of body composition, that partition the body into fat mass and fat-free mass

Abbreviations: ADP, air displacement plethysmography; BIA, bioelectrical impedance analysis; LoA, limits of agreement; TEM, technical error of measurement.

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(e.g. air displacement plethysmography (ADP) and bioelectrical impedance analysis (BIA)), reference methods are costly, time-consuming, and invasive and may not be suitable for children[13]. Although 2C models of body composition are subject to error arising from variation in fat-free mass composition[9], they are more accessible to clinicians and researchers and less burdensome on participants.

ADP is an indirect method to determine body volume, using a volumetric chamber into which a participant is introduced, by recording pressure changes under isothermal and adiabatic conditions[14]. Equations that include assumed densities of fat and lean tissues are used to calculate %FM. BIA is an indirect measure of total body water from which an empirical relationship with fat-free mass can be derived using subject-specific regression equations. Previous studies generally indicate that measures of %FM by ADP ($\%FM_{ADP}$)[11,15,16], rather than BIA ($\%FM_{BIA}$)[9,17], have better agreement with reference measures in paediatric populations. However, age, sex, BMI and BIA device all impact the estimation of %FM and should therefore be considered in %FM prediction equations[11,18].

Few studies have compared measures of %FM derived from ADP and BIA in paediatric populations[19], generally finding that $\%FM_{ADP}$ was greater than $\%FM_{BIA}$[20,21]. Whilst these studies benefit from large sample sizes, comparisons between methods were not distinguished based on weight status which can impact estimates of body composition[22]. One study which did compare $\%FM_{ADP}$ and $\%FM_{BIA}$ in both participants with and without obesity[23] measured $\%FM_{BIA}$ using a foot-to-foot device (measuring only part of the body) and $\%FM_{ADP}$ using general[24], rather than child-specific regression equations[11,25]. Comparisons between %FM methods should be made using age-specific equations, controlling for gender and weight status[16,26,27].

Reliability of %FM measurements in children have been conducted, showing intraclass correlation coefficients (ICC) of > 0·90 from BIA[12] and > 0·93 from ADP[28]. Vicente-Rodriguez *et al.*[29] reported intra-day reliability of $\%FM_{ADP}$ and $\%FM_{BIA}$ in eighty-four adolescents (13-to-17 years old). Technical error of measurement (TEM) was 1·07 % and 0·74 % for ADP and BIA respectively, with correlation coefficients of 0·989 and 0·993 for ADP and BIA, respectively. However, there is a paucity of research that has assessed the reliability of ADP and BIA methods in one cohort, with no studies investigating this in a cohort of children < 12 years.

A recent systematic review suggests that ADP has similar validity to dual-energy X-ray absorptiometry and isotopic dilution methods to assess %FM in children with obesity[30]. ADP has been considered as a 'standard' method of body composition assessment[23] to which BIA methods can be compared for validity and reliability[20,21]. Measures of body fat by ADP offers greater agreement with reference measures, but BIA offers faster, more convenient and inexpensive field-based measures of body fat. Therefore, the aim of this study was to measure concurrent validity and reliability of $\%FM_{ADP}$ and $\%FM_{BIA}$ in 6-to-12-year-old children with and without obesity. We hypothesise that $\%FM_{BIA}$ will be underestimated compared with $\%FM_{ADP}$, and that in boys with obesity, $\%FM_{BIA}$ will be underestimated to a greater extent compared with boys without obesity. Compared with studies that have not used age-specific equations for body composition, we expect to find less difference between $\%FM_{ADP}$ and $\%FM_{BIA}$. Finally, we hypothesise that both $\%FM_{ADP}$ and $\%FM_{BIA}$ methods will be reliable, in keeping with literature involving older children. The findings will help practitioners determine whether $\%FM_{ADP}$ and $\%FM_{BIA}$ can be used interchangeably and reliably in children.

Method

Participants

Seventy-one boys underwent assessment of body composition by BIA and ADP (age: 10·1 ± 1·70 years, height: 1·43 ± 0·11 m, mass: 39·4 ± 11·2 kg). Ten boys took part in the intra-day reliability analysis of BIA and ADP (age: 10·0 ± 2·63 years, height 1·39 ± 0·17 m, mass 33·8 ± 10·8 kg). This study was conducted according to the guidelines laid down in the Declaration of Helsinki, and all procedures involving human subjects/patients were approved by the host institution (Ref No. ETH/13/11). Written and verbal informed consent were obtained from parents and children (verbal consent was witnessed and formally recorded). Parents completed a health medical questionnaire prior to data collection; all participants were reportedly healthy at the time of the study. Obesity was defined as a %FM > 25 %[23].

Procedure

Participants were tested in pairs, and a randomised, crossover design was used whereby pairs were randomly assigned to be tested by either ADP or BIA, after which they completed the other test procedure immediately after the first. Each participant wore tight-fitting swimming shorts with no shoes or socks throughout both testing procedures. Participants were instructed not to eat, drink or exercise 2 h before the measurement and to void their bladder 30 min before testing. Estimates of %FM from ADP ($\%FM_{ADP}$) and BIA ($\%FM_{BIA}$) were measured within the same day by the lead author. For the assessment of reliability, $\%FM_{ADP}$, $\%FM_{BIA}$, body volume and resistance measurements were repeated within 10 min of the first test in order to avoid biological variation in hydration and temperature.

Air displacement plethysmography

ADP was measured using the Bodpod device following manufacturer's protocols[14]. Each participant wore a swim cap to cover and compress head hair. The Bodpod weighing scale was calibrated before each testing session with known 20 kg weights; all calibrations were within ±0·01kg. The chamber was calibrated against a known volume cylinder (50·024l) before each testing session. Five repeated measures of cylinder volume were made during the calibration procedure. The average estimated volume was 50·047 ± 0·007l, within the accuracy and variability range of repeated measures previously reported for volumetric measures by the Bodpod[14].

The ADP procedure involved three successive measurements of raw body volume, and the total procedure time was less than 1 min. If body volume differed by more than 0·015L between the measures, the procedure was repeated. The mean of the three

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Table 1. Equations used in ADP and BIA procedures

Equations	Reference
Used in ADP procedure	
$TGV = 0{\cdot}00056Ht^2 - 0{\cdot}02442Ht + 8{\cdot}15194$	Fields et al. (31)
$SSA = (0{\cdot}024265Wt^{0{\cdot}5378})(Ht^{0{\cdot}3964})100$	Haycock et al. (32)
$\%FM = 100\left[\left(\left(\frac{k_1}{D_b}\right) - k_2\right]\right)$	Lohman (25)
Used in BIA procedure	
$FFM = \frac{\left(3{\cdot}474 + 0{\cdot}459\frac{Ht^2}{R} + 0{\cdot}064Wt\right)}{(0{\cdot}769 - 0{\cdot}009A - 0{\cdot}016S}$	Horlick et al. (33)
$\%FM\ \frac{Wt - FFM}{Wt}\ 100$	

TGV, thoracic gas volume; *Ht*, height in cm (derived by height in m × 100); *SSA*, skin surface area; *Wt*, body mass in kg; *%FM*, percent fat mass; k_1 and k_2, sex- and age-specific constants; D_b, *body density; FFM, fat free mass; R*, resistance; *A, age in years; S*, sex-specific constants.

Table 2. Equations used to assess reliability of data

Equation	Reference
$TEM = \sqrt{\frac{\left(\sum d^2\right)}{2n}}$	
$\%TEM = \left(\frac{TEM}{x}\right)100$	
$r_{xx} = 1 - \left(\frac{TEM^2}{SD^2}\right)$	Ulijaszek & Kerr (38)
$ICC(3,k) = \frac{BMS - EMS}{BMS}$	Shrout & Fleiss (39)

TEM, technical error of measurement; *d,* difference between measurements; *n*, number of individuals measured; *x*, mean percentage fat mass (%FM); r_{xx}, reliability coefficient; *ICC*, intraclass correlation coefficient; *k,* number of measurements; *BMS*, between-subject variance; *EMS*, error (residual) mean square variance.

raw body volumes (Vb) was corrected for isothermal conditions of air in the lungs and around the skin surface. Raw Vb was corrected for thoracic gas volumes (and skin surface area) using child-specific equations detailed in Table 1. Body density was calculated by dividing the corrected body volume by body mass and converted to %FM using sex- and age-specific equations published by Lohman[25] (Table 1).

Bioelectrical impedance analysis

A multi-frequency BIA device (Quantum II, RJL systems, Inc.) was used to measure body impedance in the participants. The BIA device was calibrated before each testing session using known resistance and reactance. The device recorded mean resistance figures of 384 ± 0·34Ω and reactance of 44·9 ± 1·22Ω which were within the manufacturer's guidelines.

The participants were instructed to lay supine on a portable couch for 5 min prior to testing as per the manufacturer's instructions to allow extracellular water to level out across the body. Electrodes were placed on the ipsilateral bony prominences of the wrist and ankle (metacarpal and metatarsal lines), ensuring the electrodes were 5 cm apart.

Reactance (*X*) and resistance (R) were outputted for each participant for the calculation of %FM based on sex- and age-specific equations. The equation of Horlick *et al.*[33] was chosen to estimate FFM (Table 1) based on regression analysis of impedance measures from the same manufacturer (RJL) used in the current study and has shown to be valid in paediatric populations[19]. FFM was then converted to %FM (Table 1).

Statistical analysis

Concurrent validity. With obesity and without obesity group differences for age, height, body mass, raw body volume (m^3), resistance (Ω), $\%FM_{ADP}$ and $\%FM_{BIA}$ were assessed by independent *t* tests. Comparisons between $\%FM_{ADP}$ and $\%FM_{BIA}$ were made for the full sample and within the with obesity and without obesity groups. Differences between $\%FM_{ADP}$ and $\%FM_{BIA}$ were assessed by paired samples *t* tests. Effect sizes (ES) were calculated based on Cohen's d and defined as < 0·2 weak, 0·2 to 0·49 small, 0·5 to 0·79 medium and > 0·79 large[34].

Pearson's correlation coefficients were performed to measure the strength of association between $\%FM_{ADP}$ and $\%FM_{BIA}$, with 95 % CI. Correlation coefficients < 0·29 were defined as weak, between 0·3 and 0·49 moderate, and > 0·5 strong[34]. Agreement between $\%FM_{ADP}$ and $\%FM_{BIA}$ were analysed using Bland–Altman analysis[35]. This involved the calculation of the mean difference between two methods together with limits of agreement (LoA), based on 95 % CI, calculated from the standard deviation of the mean difference for each participant (multiplied by 1·96). Proportional bias and error affected by the magnitude of measurement were determined by Pearson's correlation coefficient $r > 0{\cdot}5$[36]. Predicting $\%FM_{ADP}$ is considered as the 'standard' method for this study, to which $\%FM_{BIA}$ was compared. To address clinical acceptability, a minimal acceptable standard for estimating %FM of ± 3·5 % (group-level difference) from the reference measure was employed[37]. The sample size of 71 was calculated based on the minimal acceptable standard[37], standard error of measurement for BIA[12], with 80 % power and two-sided significance of 0·05.

Reliability. For comparison with previous literature on the reliability of %FM measures, three reliability statistics were calculated: technical error of the measurement (TEM and TEM%), coefficient of reliability (r_{xx}) and ICC as detailed in Table 2.

Results

Table 3 presents data for all participants and for the with obesity and without obesity groups. No significant differences were found between groups for age ($t_{(69)} = 1{\cdot}85$, $P = 0{\cdot}069$), height ($t_{(69)} = 1{\cdot}09$, $P = 0{\cdot}212$) and resistance ($t_{(69)} = 0{\cdot}32$, $P = 0{\cdot}748$). The with obesity group was significantly heavier ($t_{(69)} = 2{\cdot}36$, $P = 0{\cdot}021$), had a higher BMI ($t_{(69)} = 4{\cdot}97$, $P < 0{\cdot}001$), greater raw body volume ($t_{(69)} = 0{\cdot}75$, $P = 0{\cdot}004$), and a higher $\%FM_{ADP}$ ($t_{(69)} = 14{\cdot}15$, $P < 0{\cdot}001$) and $\%FM_{BIA}$ ($t_{(69)} = 8{\cdot}80$, $P < 0{\cdot}001$).

Concurrent validity

Table 4 presents the mean difference and LoA of $\%FM_{ADP}$ and $\%FM_{BIA}$ for all participants, the with obesity group, and the without obesity group. Compared with $\%FM_{BIA}$, $\%FM_{ADP}$ was significantly higher in all participants ($t_{(70)} = 5{\cdot}11$,

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Table 3. Age and anthropometric variables according to weight status

	All participants (*n* 71)		Without obesity (*n* 46)		With obesity (*n* 25)	
	Mean	SD	Mean	SD	Mean	SD
Age (years)	10·1	1·70	10·3	1·94	9·56	0·96
Mass (kg)	39·4	11·2	37·1	11·0	43·5	10·6*
Height (m)	1·43	0·11	1·42	0·12	1·43	0·07
BMI (kg/m^2)	18·7	3·70	17·3	2·76	21·2	3·83*
Raw body volume (m^3)	36·6	10·9	34·0	10·2	41·5	10·7*
Resistance (Ω)	674	96·2	677	101	669	89·5
%FM$_{ADP}$	21·6	9·00†	16·1	4·03†	32·2	5·49*,†
%FM$_{BIA}$	18·2	8·87	13·7	6·14	27·0	6·59*

%FM$_{BIA}$, percentage body fat measured by bioelectrical impedance analysis; %FM$_{ADP}$, percentage body fat measured by air displacement plethysmography.
* Significant difference between non-obese and obese groups at 0·05 level.
† Significant difference within group between ADP and BIA methods at 0·05 level.

Table 4. Differences in %FM measured by ADP and BIA (%FM$_{BIA}$–%FM$_{ADP}$)

	All participants (*n* 71) %FM	Without obesity (*n* 46) %FM	With obesity (*n* 25) %FM
Mean	−3·38	−2·40	−5·20
SD	5·60	5·45	5·46
95 % CI	−4·30, −2·46	−3·51, −1·28	−6·71, −3·68
LoA	−14·5, 7·78	−13·3, 8·50	−16·1, 5·73

%FM, percentage fat mass; LoA, limits of agreement.

$P<0{\cdot}001$, ES = 0·42) and in the without obesity group ($t_{(45)}=2{\cdot}98$, $P=0{\cdot}005$, ES 0·52; Table 3); although mean differences observed were clinically acceptable (< 3·5 %), LoA were 22·3 % and 21·8 % in all participants and those without obesity, respectively. In the with obesity group, %FM$_{ADP}$ was significantly higher compared with %FM$_{BIA}$ ($t_{(24)}=4{\cdot}76$, $P<0{\cdot}001$, ES = 0·90; Table 3), with the mean difference (-5·20 ± 5·46 %) exceeding the clinically acceptable threshold of 3·5 %, and LoA of 21·8 %. A strong, significant positive correlation was found between %FM$_{ADP}$ and %FM$_{BIA}$ when examining all participants ($r=0{\cdot}80$, $P<0{\cdot}001$, 95 % CI 0·64 to 0·95) and participants with obesity ($r=0{\cdot}60$, $P=0{\cdot}001$, 95 % CI 0·11 to 1). In the without obesity group, a moderate, significant positive correlation was found ($r=0{\cdot}44$, $P=0{\cdot}003$, 95 % CI 0·26 to 1). Figure 1 presents Bland–Altman plots of %FM$_{ADP}$ and %FM$_{BIA}$ for all participants, those with obesity and those without obesity. No proportional bias was detected ($r=0{\cdot}001$), meaning agreement between measures was not affected by the magnitude of %FM.

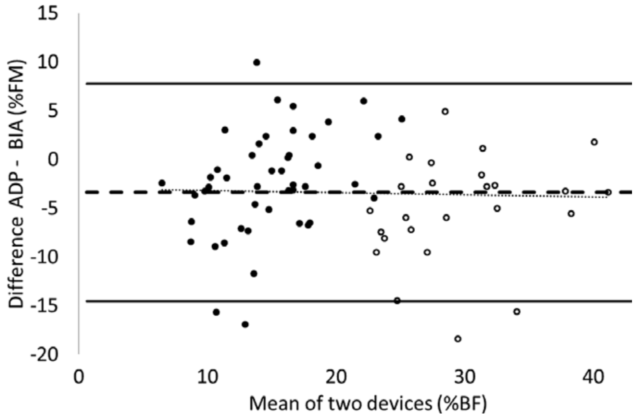

Fig. 1. Bland–Altman plot of percentage fat mass (%FM) from ADP and BIA. Black circles represent the without obese group, and open circles represent the with obesity group. Dashed line is mean difference (bias), and solid lines are limits of agreement (± 1·96 SD). Dotted line is the line of best fit (proportional bias). ADP, air displacement plethysmography; BIA, bioelectrical impedance analysis.

Reliability

Reliability analysis revealed that ADP resulted in lower error of % FM measures compared with BIA; TEM of 0·55 % and 0·65 %, respectively. Coefficient of reliability and ICC were also higher in %FM$_{ADP}$ measures (0·92 and 0·95 for r_{xx} and ICC, respectively) compared with %FM$_{BIA}$ measures (0·89 and 0·93; Table 5).

Discussion

The aim of this study was to compare validity of %FM$_{BIA}$ to the 'standard' %FM$_{ADP}$ and assess intra-day reliability of both methods in the same cohort. Compared with ADP, BIA underestimated %FM in the study population, but there was no bias in differences between methods relating to obesity status (i.e. magnitude of %FM). Despite the significant correlation, there was a significant difference and large LoA between measures of %FM$_{BIA}$ and %FM$_{ADP}$. The reliability findings reported in this study reveal that %FM$_{ADP}$ is a more reliable measure compared with %FM$_{BIA}$, but both methods were highly reliable in the cohort.

Concurrent validity

Underestimation of %FM$_{BIA}$ compared with %FM$_{ADP}$ in the current study is in general agreement with previous studies[20,21,23,40]. Previous studies have shown %FM$_{BIA}$ to be underestimated by 0·5–5·6 % in children and adolescents compared with %FM$_{ADP}$, although some %FM$_{BIA}$ prediction equations have resulted in an overestimation[21]. The mean underestimation of 3·4 % found in the present study is within the range previously reported. The differences between %FM$_{BIA}$ and %FM$_{ADP}$ within the with and without obesity groups also agree with Azcona *et al.*[23] who reported mean

Table 5. Mean, SD and within-day test–retest for intra-day reliability of %FM measures (*n* 10)

	Session 1		Session 2						
	Mean	SD	Mean	SD	TEM	TEM%	r_{xx}	ICC	95 % CI
$\%FM_{BIA}$	11·4	7·92	12·5	7·86	0·65	–	0·89	0·93	0·78, 0·98
$\%FM_{ADP}$	13·3	9·16	14·1	8·17	0·55	–	0·92	0·95	0·85, 0·98
Resistance (Ω)	670	83·3	685	71·3	5·72	1·63	0·90	0·95	0·85, 0·98
Raw body volume (m^3)	30·7	10·3	30·8	10·2	0·11	0·34	0·92	0·99	0·98, 1·00

$\%FM_{BIA}$, percentage body fat measured by bioelectrical impedance analysis; $\%FM_{ADP}$, percentage body fat measured by air displacement plethysmography; TEM, technical error of measurement; ICC, intraclass correlation coefficient.
TEM% is not presented for %FM since the units are already a percentage

underestimation of $\%FM_{BIA}$ compared with $\%FM_{ADP}$ among the full sample (3·39 %), without obese (2·49 %) and with obesity groups (5·01 %). Despite different BIA devices and %FM equations used between the current study and Azcona *et al.* [23], the mean differences between $\%FM_{BIA}$ and $\%FM_{ADP}$ are similar.

Compared with the clinically acceptable differences reported by Heyward and Wagner[37], %FM differences in the without obesity group were within the ± 3·5 % clinically acceptable threshold, but in the with obesity group differences would be deemed clinically unacceptable (> 3·5 %). Despite no significant bias in differences between devices detected across levels of body fat, it does appear that BIA underestimates %FM to a greater extent. Furthermore, the LoA found in the current study are in general agreement with values of 15·3–20·6 % reported in previous studies[20,21,23]. Whilst no consensus has been reached on what level of LoA is clinically acceptable (a range of 2 to 20 % has been reported in the literature)[30,41,42], the large LoA in the current study indicates that BIA and ADP cannot be used interchangeably to measure an individual's %FM. Assessment of body composition must be accurate on an individual basis to correctly identify overweight and obesity[43].

Reliability

The findings from the current study suggest that repeated measurements of %FM from ADP and BIA are highly reliable in young children. These findings are comparable to other studies examining the intra-day reliability of $\%FM_{ADP}$ and $\%FM_{BIA}$ in older children. Vicente-Rodriguez *et al.*[29] measured intra-day reliability in eighty-four adolescents (13–17 years old), finding $\%FM_{ADP}$ TEM of 1·07 % FM and $r_{xx} = 0·99$, and $\%FM_{BIA}$ TEM of 0·74 % and $r_{xx} = 0·99$. Resistance and body volume reliability in the current study also compared well with values of Vicente-Rodriguez *et al.*[29], resistance TEM of 10·2Ω and $r_{xx} = 0·99$, and body volume TEM of $0·58m^3$ and $r_{xx} = 0·99$. Comparable reliability in the current younger cohort to adolescents reveals that children were able to adhere to the BIA and ADP procedures and follow instructions.

The intra-day reliability of body fat mass measures from ADP and BIA are dependent on environmental conditions, instructor competence and participant adherence to the procedures. Environmental variation includes pressure changes within the laboratory (from opening doors or drafts) during the procedure that can affect ADP reliability and, temperature changes in 10 min between repeated measures that can affect BIA reliability. Correct electrode placement on the ipsilateral bony prominences of the wrist and ankle (the metacarpal and metatarsal lines)[44] can be subjective. Electrode placement variability can alter impedance readings by 4 %[45] and would have reduced reliability in this study. Variability due to procedural adherence includes movement of the participant in the Bodpod chamber or irregular breathing. These can cause pressure changes within the Bodpod influencing raw body volumes[46]. For this reason, ADP measures from Bodpod were taken in triplicate and, if the raw body volumes differed by > 0·015L, the procedure was started again. In order to maximise intra-day reliability of $\%FM_{ADP}$ and $\%FM_{BIA}$ measures environmental conditions, protocols and participant preparation should be strictly monitored throughout testing procedures.

Limitations of the current study comprise the use of predicted lung volumes in ADP measurements which may impact the accuracy of $\%FM_{ADP}$. However, young children struggle with the protocol for lung volume measurement, and error in the correction of raw body volume for air in the lungs is relatively small[47]. Other age- and sex-specific %FM equations are available for ADP that account for changes in hydration status with age and sex[11]. However, the Lohman[25] equation has been validated against 4C[48] and, in boys, compares well with more recent equations for $\%FM_{ADP}$[11]. The relatively short duration of food and drink abstention may have affected BIA measurements. However, longer abstention may be unethical and impractical[49]. We could not collect pubertal status from our sample, and it is acknowledged that pubertal status may have improved the accuracy of both $\%FM_{ADP}$ and $\%FM_{BIA}$. Particularly for $\%FM_{BIA}$ measurements, puberty/maturation status has an impact on total body water, but the current study used standardised procedures and age-appropriate equations to limit extraneous variation. Indeed, as reported by Horlick *et al.*[33] when developing the BIA equation used in the current study, including Tanner stage to the regression model for total body water had little effect on the predictive power above measures of age, height, mass and sex.

Conclusion

The results of the intra-day reliability tests revealed that both $\%FM_{ADP}$ and $\%FM_{BIA}$ are highly reliable in boys aged 6-to-12 years. $\%FM_{BIA}$ was significantly correlated with $\%FM_{ADP}$ in children with and without obesity. However, $\%FM_{BIA}$ was significantly underestimated in both groups, but only in the with obesity group was it beyond the minimal acceptable standard of ± 3·5 %. Therefore, BIA may be suitable for determining %FM in boys without obesity aged 6-to-12 years. Similar to the findings of previous studies that have used different devices (e.g. foot-to-foot BIA), %FM equations (proprietary or adult), and sample age (e.g. adolescents) and do not consider obesity status, the large LoA between $\%FM_{ADP}$ and $\%FM_{BIA}$ in the current study indicate that the devices cannot be used interchangeably in boys aged 6 to 12 years.

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