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Evaluation of two foot-to-foot bioelectrical impedance analysers to assess body composition in overweight and obese adolescents

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The objective of the present study was to determine the accuracy of two foot-to-foot (FF) bioelectrical impedance analysers (BIA) to assess body composition in overweight and obese adolescents, compared with dual-energy X-ray absorptiometry (DXA) and hand-to-foot (HF) BIA. Body composition was assessed in fifty-three overweight or obese adolescents (BMI 27·9 (SD 4·1) kg/m^2; aged 13–16 years) by DXA (Hologic QDR-4500; Hologic Inc., Bedford, MA, USA) and BIA (HF (BIA 101, RJL System, Detroit, IL, USA) and FF (Body Fat Monitor Scale BF-625, Tanita Corporation of America Inc., Arlington Heights, IL, USA; Téfal Bodymaster Vision, Téfal, Rumilly, France)). Bland–Altman tests showed that, compared with DXA, FF-Tanita and FF-Téfal underestimated ($P<0·05$) fat mass (FM) less than HF-BIA (−1·7 (SD 3·1), −0·7 (SD 5·8) and −2·3 (SD 2·2) kg respectively, $P<0·001$). However, the limits of agreement between DXA and FF-Tanita or FF-Téfal were much greater than those obtained with HF-BIA (−7·7 and +4·3, −12·0 and +10·6 *v.* −2·1 and +6·7 kg respectively). The differences between FM assessed using the FF-Tanita or the FF-Téfal analyser and DXA increased with the waist:hip ratio, and were higher in boys than in girls. The major limiting factor of FF-BIA was the inter-individual variability in FM estimates. In conclusion, FF-BIA and DXA are not interchangeable methods. FF-BIA could be acceptable to assess body composition in large groups of overweight or obese adolescents, but cannot be recommended for body composition assessment in obese subjects because of the large errors in individual estimates.

Obesity: Body composition: Foot-to-foot bioelectrical impedance analysis: Dual-energy X-ray absorptiometry

Simple, rapid, and accurate measurement of body composition is frequently required for the medical and nutritional follow-up of obese children and adolescents, especially during a weight-reduction period. For this reason, bioelectrical impedance analysis (BIA) has become a popular method in research laboratories, hospitals, private clinics and wellness centres to assess body composition across a spectrum of ages and body weights (BW; National Institutes of Health Technology, 1996). BIA is a safe, non-invasive and portable method used for assessing body composition from the estimate of total body water. However, several factors limit its valid application to severely obese people: body geometry and body water distribution are altered, while the hydration factor of fat-free mass (FFM) is higher in obese than in non-obese subjects (Waki *et al.* 1991; Deurenberg, 1996; Wells *et al.* 1999).

Conventional BIA systems, called hand-to-foot (HF) BIA, require four gel electrodes placed on the upper and lower limbs and the subject has to lie supine for 30 min before measurements. However, the new foot-to-foot (FF) BIA analysers are much more convenient, since the subject only needs to stand barefoot on the scale for simultaneous measurements of BW and impedance across the lower limbs. Gender, age and height are entered manually into the system via a digital keyboard, and the subject's fat mass (FM) or % FM is displayed immediately.

Because of its convenience, FF-BIA has become increasingly popular with health professionals, as well as the general public, for the assessment and monitoring of body composition. Several studies have shown FF-BIA to be a useful alternative method to the conventional HF-BIA tetrapolar system (Nunez *et al.* 1997; Jebb *et al.* 2000). However, FF-BIA measures only the impedance of the lower part of the body, although the legs contribute about one-third to BW. In contrast, the trunk contributes to half of BW, and only 10–20 % to total body impedance in lean

Abbreviations: BIA, bioelectrical impedance analyser; BW, body weight; DXA, dual-energy X-ray absorptiometry; FF, foot-to-foot; FM, fat mass; FFM, fat-free mass; HF, hand-to-foot.

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subjects (Foster & Lukaski, 1996). Therefore, specific prediction equations should be used for obese subjects, because predictive equations developed in normal-weight subjects generally underestimate FM (Deurenberg, 1996) in obese adults and children (Ellis, 1996; Eisenkolbl *et al.* 2001). Nevertheless, few studies have validated FF-BIA against reference methods such as hydrodensitometry, total body water, dual-energy X-ray absorptiometry (DXA), or a four-compartment model, in obese or non-obese adults (Bell *et al.* 1998; Utter *et al.* 1999; Jebb *et al.* 2000; Swartz *et al.* 2002) and children (Sung *et al.* 2001; Tyrrell *et al.* 2001). The mean differences in FFM, FM and % FM between FF-BIA and each of these reference methods is generally low and acceptable for large groups of subjects, but individual errors are high, especially for % FM. Furthermore, the prediction equations must be validated on each FF-BIA analyser, and for each population for which it is to be used (Tyrrell *et al.* 2001).

The objective of the present study was, therefore, to test the accuracy of two commercial FF-BIA machines to assess FM and FFM in overweight and obese adolescents, compared with DXA and HF-BIA.

Subjects and methods

Study design

Fifty-three overweight or obese adolescents (twenty boys and thirty-three girls) aged 13–16 years participated in this study. The volunteers were recruited from the Paediatrics Department of the Clermont-Ferrand Hospital, France. The purpose and potential risks and benefits were carefully explained to each subject and his or her parents. Written informed consent was obtained from all adolescents and their parents. The experimental protocol was approved by the University Ethical Committee on Human Research for Medical Sciences (AU no. 361). Subjects were examined clinically and were regarded as healthy. Pubertal status was ascertained using line drawings and written descriptions of the five stages of puberty according to Tanner's (1961) definitions. Subjects were excluded if they were taking any medications that would alter body water content.

Physical characteristics and body composition

A series of body composition measurements, including anthropometric measurements, FF-BIA, HF-BIA and DXA, were performed by the same person after an overnight fast. BW was measured to the nearest 0·1 kg using a calibrated manual weighing scale (Seca 709, Hamburg Germany). Adolescents were asked to remove all jewellery and clothing except underwear. Height was measured to the nearest 5 mm on a standardized wall-mounted height board. Circumferences at the waist and hips were measured in triplicate to the nearest 1 mm using a steel tape and according to the position presented in the atlas of Sempé *et al.* (1979). The waist:hip ratio was calculated by dividing the waist circumference by the hip circumference.

BW and FM or % FM were measured simultaneously using two FF-BIA machines: Tanita (Body Fat Monitor Scale, BF-625; Tanita Corporation of America Inc., Arlington Heights, IL, USA) and Téfal (Téfal Bodymaster Vision; Téfal, Rumilly, France). Gender, age and height were entered manually into the keypad interface. The FF-BIA equipment had two stainless-steel foot-pad electrodes mounted on a platform scale. The electrodes for each foot were subdivided into anterior and posterior electrodes. A current was applied through the anterior portion of the foot-pad electrodes and the voltage drop was measured in the posterior portion of the foot-pad electrodes. The impedance measurement used a 50 kHz–500 μA current. The voltage drop and the BW signal were converted to digital data using an analogue to digital converter.

Body composition was also assessed by HF-BIA (BIA 101; RJL System, Detroit, IL, USA) after 30 min in a supine position, and by DXA (Hologic QDR-4500 and version 9.10 of total body scan software; Hologic Inc., Bedford, MA, USA). The subject was supine on the bed and was scanned from head to toe. The total body scan provided values for total body bone mineral content, non-bone lean tissue and FM in arms, legs, trunk and head separately, and in the whole body. FFM was defined as the sum of non-bone lean tissue and bone mineral content. Hydration of FFM was assumed to be constant (73·2 %).

Statistical analyses

Statistical analyses were performed using Statistica for Windows (Kenel version 5.5 A, StatSoft 1984–2000; Statsoft Inc., Maisons-Alfort, France). ANOVA and *t* tests were used to study the effects of gender on the anthropometric characteristics and body composition of the adolescents. Bland–Altman analysis (Bland & Altman, 1986) was used to test for bias (mean difference) and limits of agreement between FM or % FM assessed by FF-BIA (using either the Tanita or the Téfal analyser), HF-BIA or DXA. The four sets of FM and % FM scores were compared using paired *t* tests. Significance was set at $P<0·05$ The results are presented as mean values and standard deviations.

Results

Subjects characteristics

The physical characteristics of subjects are shown in Table 1. Among the fifty-three subjects, forty-six had a BMI >97th, five >95th and two >85th percentile for gender and chronological age of the French adolescent population (Rolland-Cachera *et al.* 1991). BW was 51–131 kg, BMI 22·6–38·7 kg/m^2, FFM (as assessed by DXA) 33·1–87·0 kg, FM 13·6–49·8 kg and % FM 21·4–47·7. Girls were 1·1 years older than boys ($P<0·01$) However, there were no significant differences in height, BW and BMI between boys and girls, although boys tended to be taller than girls ($P<0·10$) Waist circumference was similar in boys and girl, but hip circumference was significantly lower in boys than in girls ($P<0·007$) Consequently, the waist:hip ratio was significantly higher in boys than in girls ($P<0·001$) FFM was significantly

Table 1. Physical characteristics and body composition of adolescents as assessed by dual-energy X-ray absorptiometry*†
(Mean values and standard deviations)

	Boys (n 20)		Girls (n 33)		Statistical significance of effect of gender: P
	Mean	SD	Mean	SD	
Age (years)	14·1	1·4	15·2	1·4	0·010
Weight (kg)	78·7	19·0	77·3	12·1	0·744
Height (m)	1·695	0·093	1·649	0·097	0·098
BMI (kg/m^2)	27·2	4·9	28·4	3·5	0·313
Waist circumference (m)	0·958	0·114	0·954	0·126	0·901
Hip circumference (m)	0·953	0·089	1·021	0·085	0·007
Waist:hip ratio	1·00	0·05	0·93	0·05	0·001
FFM (kg)	55·9	14·2	49·1	7·3	0·025
FM					
kg	22·8	7·3	28·3	7·0	0·009
%	29·1	5·7	36·3	4·6	0·001

FFM, fat-free mass; FM, fat mass.
* For details of procedures, see p. 988.
† The study power (1 − β, the type II error) was >0·95.

higher in boys than in girls ($P<0·03$) whereas FM and % FM were significantly lower ($P<0·001$) However, puberty status was not a significant factor in body composition.

Comparison of head-to-foot and foot-to-foot bioelectrical impedance analysis with dual-energy X-ray absorptiometry

BW determined with the three balances were significantly different (77·8 (SD 14·9), 77·6 (SD 14·9) and 78·0 (SD 15·1) kg for Tanita, Téfal and Seca 709 balances respectively, $P<0·001$). Compared with DXA, HF-BIA overestimated FFM by 2·3 (SD 2·3) kg, but underestimated FM and % FM by 2·3 kg and 2·9 % respectively ($P<0·05$) The biases (mean differences) for FM and % FM and the limits of agreement between the two methods (Bland–Altman test; Bland & Altman, 1986) are shown in Table 2. However, the biases and standard deviations were similar for boys and girls and did not vary with FM (Fig. 1(a)) or % FM (results not shown).

Table 2. Limits of agreement of differences for fat mass (kg) and % fat mass between hand-to-foot bioelectrical impedance analysis (BIA), foot-to-foot BIA using the Tanita and Téfal analysers, and dual-energy X-ray absorptiometry*†

	Difference	SD	Limits of agreement		P‡
HF-BIA, FM					
kg	−2·3	2·3	2·1	−6·7	0·001
%	−2·9	2·8	2·5	−8·4	0·001
FF-Tanita, FM					
kg	−1·7	3·1	4·3	−7·7	0·001
%	−2·5	4·2	5·7	−10·6	0·001
FF-Téfal, FM					
kg	−0·7	5·8	10·6	−11·9	0·399
%	−1·8	7·6	13·1	−16·7	0·096

HF, hand-to-foot; FM, fat mass; FF, foot-to-foot.
* For details of subjects and procedures, see Table 1 and p. 988.
† BIA 101, RJL System, Detroit, IL, USA; Body Fat Monitor Scale BF-625, Tanita Corporation of America Inc., Arlington Heights, IL, USA; Téfal Bodymaster Vision, Téfal, Rumilly, France; Hologic QDR-4500, Hologic Inc., Bedford, MA, USA, respectively.
‡ Paired t tests between FM as assessed by dual-energy X-ray absorptiometry and FM assessed by HF-BIA or FF-BIA.

Compared with DXA, FF-BIA also underestimated FM ($P<0·001$) With the Tanita analyser, the differences averaged −3·7 (SD 3·6) (range −8·5 to +4·2) kg in boys and −0·5 (SD 2·0) (range −5·3 to +3·0) kg in girls. The differences were greater with the Téfal analyser: −5·0 (SD 6·9) (range −12·3 to +11·1) kg in boys and +1·9 (SD 2·7) (range −10·1 to +7·4) kg in girls. For the whole population of boys and girls, the mean differences (biases) of FM and % FM as assessed by FF-BIA and DXA were relatively low, lower than with HF-BIA ($P<0·05$). However, the standard deviations of the differences were much higher than with HF-BIA. Consequently, the limits of agreement between DXA and FF-BIA were large, especially with the Téfal analyser. They were much greater than those obtained with HF-BIA (Table 2). Thus, FF-BIA and HF-BIA could not be considered as interchangeable methods. Furthermore, the Bland–Altman (Bland & Altman, 1986) plots showed that the bias varied greatly with FM. Compared with DXA, the Tanita and Téfal analysers underestimated low FM and % FM <25–30 (mainly boys), but overestimated high FM and % FM >25–30 (mainly girls; Fig. 1 (b and c)).

The distribution of FM in the body of overweight and obese subjects varies with the type of obesity (android *v.* gynoid). This can be characterized by the waist:hip ratio. The modifications of FM distribution can affect the accuracy of body composition assessment by FF-BIA, compared with HF-BIA or DXA. Therefore, the differences between FM (kg) assessed using the Tanita or the Téfal analyser, and DXA, were plotted as a function of the waist:hip ratio (Fig. 2). The differences increased with the waist:hip ratio, especially with the Téfal analyser, and were consequently higher in obese boys than in obese girls. For waist:hip ratios about 1·05, they ranged from −8·5 to +4·2 kg FM with the Tanita analyser and from −12·3 to +11·1 kg FM for the Téfal analyser (Fig. 2).

Discussion

The results of the present study showed that FF-BIA (using the Tanita or the Téfal analyser), HF-BIA and DXA were not interchangeable methods to assess body composition in

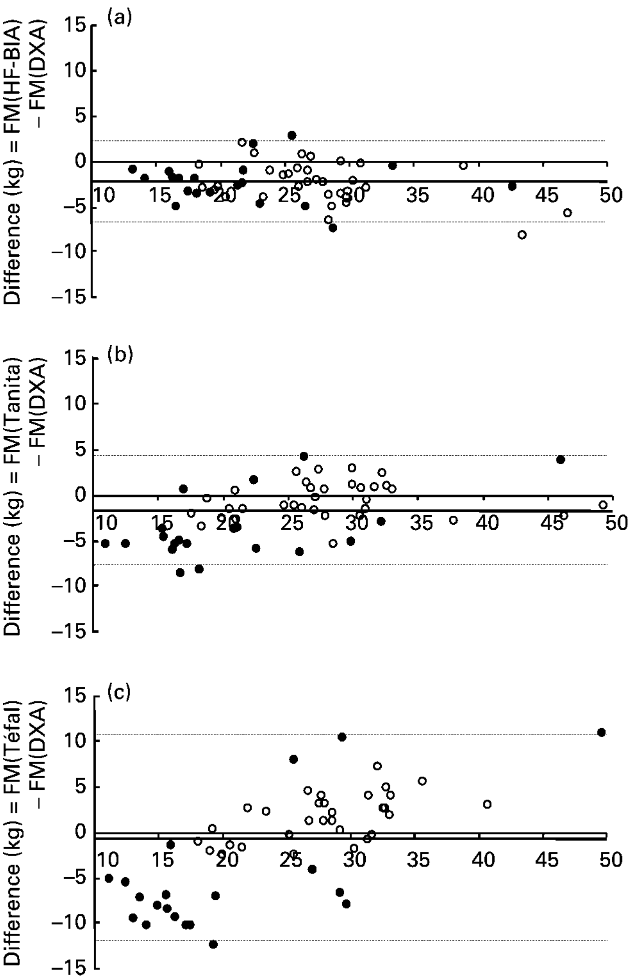

Fig. 1. Bland–Altman plots (Bland & Altman, 1986) to compare fat mass (FM) measured by different methods in boys (•) and girls (○). (a), Dual-energy X-ray absorptiometry (DXA; Hologic QRD 4500; Hologic Inc., Bedford, MA, USA) and hand-to-foot (HF) bioelectrical impedance (BIA; BIA 101; RJL System, Detroit, IL, USA), mean value = 1/2(FM(HF-BIA) + FM(DXA)); (b), DXA and Tanita (Body Fat Monitor Scale BF-625; Tanita Corporation of America Inc., Arlington Heights, IL, USA), mean value = 1/2(FM(Tanita) + FM(DXA)); (c), DXA and Téfal (Téfal Bodymaster Vision; Téfal, Rumilly, France), mean value = 1/2(FM(Téfal) + FM(DXA)). —, Mean value; ......, + or −2SD. For details of subjects and procedures, see Table 1 and p. 988.

obese adolescents. Although the biases could be acceptable for a large population of obese and overweight adolescents, the limits of agreement between FF-BIA and DXA were too large to enable satisfactory assessment of body composition in individual subjects. In addition, compared with DXA, the Tanita and Téfal analysers underestimated low FM and % FM, but overestimated high FM and % FM. Furthermore, the differences were greater in boys than in girls, and increased with the waist:hip ratio, indicating that FM and % FM were strongly underestimated in adolescents exhibiting android obesity.

The gender ratio of the sample of fifty-three volunteers who participated in the present study was the same as that of all patients (*n* 388) seen by the Paediatrics Department in 2000–2003 (%): boys 37·4; girls 62·6.

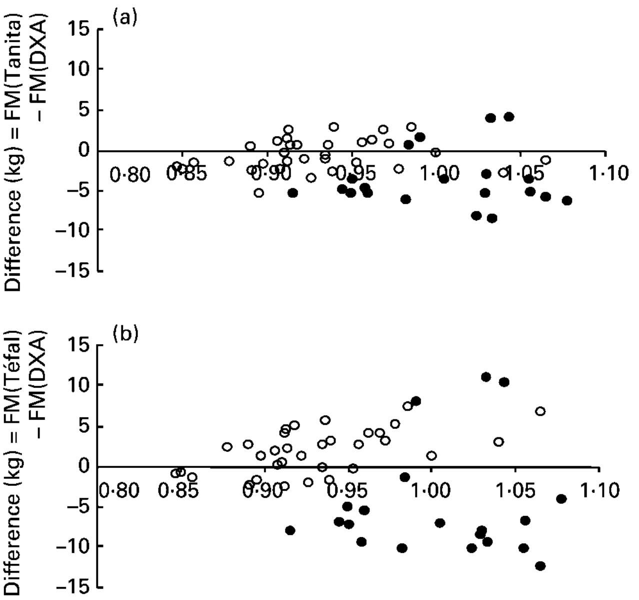

Fig. 2. Bland–Altman plots (Bland & Altman, 1986) to compare fat mass (FM) measured by different methods in boys (•) and girls (○) as a function of waist:hip ratio. (a), Dual-energy X-ray absorptiometry (DXA; Hologic QRD 4500; Hologic Inc., Bedford, MA, USA) and Tanita (Body Fat Monitor Scale BF-625; Tanita Corporation of America Inc., Arlington Heights, IL, USA); (b), DXA and Téfal (Téfal Bodymaster Vision; Téfal, Rumilly, France). For details of subjects and procedures, see Table 1 and p. 988.

Limitations of methods

As in the present study, DXA has often been used as a reference method to assess body composition because of the relatively quick scan time, the minimal radiation dose, the accuracy and the good reproducibility of measurements in adults (Jensen *et al.* 1995; Deurenberg *et al.* 2001), and in non-obese (Ellis *et al.* 1994, 1999; Goran *et al.* 1996; Boot *et al.* 1997; Dezenberg *et al.* 1999) and obese (Eisenkolbl *et al.* 2001; Taylor *et al.* 2002) children in clinical and research settings. DXA has been validated against hydrodensitometry (Tataranni & Ravussin, 1995) and direct chemical analysis in piglets and pigs (Svendsen *et al.* 1993; Mitchell *et al.* 1996; Pintauro *et al.* 1996; Fusch *et al.* 1999). The CV of repeated measurements of FFM in the same subjects averaged 2 % (Mazess *et al.* 1990; Pritchard *et al.* 1993) and the differences in FFM between DXA and chemical analyses were not significant (Svendsen *et al.* 1993) or averaged 3·5 % (Mitchell *et al.* 1996). Differences in tissue hydration have a small effect on FM estimation: hydration changes of 1–5 % would result in errors of <1 % (Pietrobelli *et al.* 1998). In addition, the bias and limits of agreement between DXA and a four-compartment model for assessing FM in 13·0 (SD 1·9)-year-old girls were independent of age and body fatness (Wong *et al.* 2002).

The absolute values of FM (kg) and % FM would have been lower, and FFM would have been higher, if Lunar equipment (Lunar Radiation Corp., Madison, WI, USA) had been used in place of the Hologic equipment. Indeed, whole-body FM and % FM of thirteen healthy young adults males were 1152 (SD 1395) g, and 1·5

(SD 1·7) % lower, and FFM was 1781 (SD 1859) g higher with Lunar than with Hologic equipment (Modlesky *et al.* 1996). Consequently, the mean differences in FM, % FM and FFM between DXA-Lunar and HF-BIA or FF-BIA would have been lower than with the Hologic equipment. Nevertheless, the individual differences and the limits of agreement of differences would have been similar, and the conclusion of the study would not have been different.

Assessment of body composition by BIA is based on the determination of total body water content from body resistance and reactance measurements (Lukaski, 1996). Various prediction equations for FFM have been published, and they assume that the water content of FFM averages 73·2 %. However, this assumption is not valid for children, since the water content of FFM assessed using the three- or four-compartment models averaged 75–76 % (Boileau *et al.* 1984). Using the reference hydration factor (73·2 %) results in an overestimation of FFM and an underestimation of FM in obese subjects. Furthermore, the proportion of extracellular water to total body water is higher in obese than in non-obese subjects (Waki *et al.* 1991). At the often-used frequency of 50 kHz (as with the tested HF-BIA and FF-BIA analysers) the current does not fully penetrate the cell membrane. Therefore, BIA measures mainly extracellular water plus partly intracellular water, and consequently overestimates FFM and underestimates FM in obese subjects (Deurenberg, 1996).

In addition, because of its relative shortness and its large cross-section compared with those of legs and arms, the trunk contributes 9 % to total body resistance compared with 48 % for legs and 43 % for arms, and 10–20 % to total body impedance, whereas it contributes 49 % to BW (Deurenberg, 1996; Foster & Lukaski, 1996). Consequently, changes in the geometry of the trunk will hardly affect body impedance and estimates of body composition. The body geometry of obese subjects is different from that of lean subjects because of the importance of abdominal FM. Consequently, using existing predictive equations established from a large population with varied body compositions to assess body composition in obese subjects would result in an underestimation of FM, especially in subjects exhibiting android obesity.

During FF-BIA measurements, the electrical current short-circuits most of the trunk tissues (Foster & Lukaski, 1996), especially the abdominal FM. Consequently, total body FM may be underestimated. FM in thighs and hips may be better taken into account than abdominal FM, which could explain why the differences between FM assessed by FF-BIA and DXA increased with the waist:hip ratio in the present study. In addition, although the mean differences in FM and % FM between FF-BIA and DXA were lower than between HF-BIA and DXA, the differences varied with FM and body geometry; consequently, the standard deviations and the limits of agreement were greater.

The prediction equations used in the HF-BIA and FF-BIA analysers used in the present study are unknown. However, the prediction equations of FFM from BIA measurements have generally been validated against densitometry, assuming that FFM density averaged 1·100. However, FFM density averaged 1·0864 (SD 0·0074) in 9–12-year-old children because of its higher water content (75·3 (SD 2·2) %), lower mineral content (4·02 (SD 0·37) %) of FFM and the high inter-individual variability of mineral, protein and water contents (CV 9·1, 11·4 and 2·9 % respectively; Wells *et al.* 1999). This explains the poor agreement between the values of FFM assessed by BIA or by a four-compartment model (Wells *et al.* 1999).

Reliability of the foot-to-foot bioelectrical impedance analysers

The mean differences in FM and % FM obtained with the Tanita and Téfal FF-BIA analysers, and DXA were relatively low and acceptable for assessment of body composition of groups of overweight and obese subjects. However, the differences were much greater in boys than in girls, probably because of differences in the type of obesity. Furthermore, individual errors were large, in agreement with the results of previous studies in lean or obese adults, children or adolescents (Utter *et al.* 1999; Jebb *et al.* 2000; Sung *et al.* 2001; Tyrrell *et al.* 2001; Swartz *et al.* 2002). The major limiting factor of FF-BIA is the inter-individual variability of the differences in FM, and especially % FM, with reference methods given by these authors: the lower and higher limits of agreement between the methods are of the order of −8, −10 and +8, +10 % FM. In the present study, the limits of agreement between the Tanita analyser and DXA were similar to those obtained in the studies quoted earlier, but they were much higher with the Téfal analyser.

In conclusion, assessment of body composition and its variation must be accurate to manage overweight and obesity in adolescents, and their physiological, pathological and social consequences. In spite of the good repeatability of measurements (Tyrrell *et al.* 2001), FF-BIA with the Tanita and the Téfal analysers tested in the present study cannot be recommended for assessment of body composition of individual overweight or obese adolescents because of the large errors in individual estimates.

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