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ORIGINAL ARTICLE

Variations in truncal body circumferences affect fat mass quantification with bioimpedance analysis

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Objective: To test the hypothesis that variations in trunk circumferences influence the accuracy of bioimpedance analysis (BIA) for assessment of percent fat mass (%FM).
Subjects and Methods: %FM was predicted with BIA, and compared with air-displacement plethysmography (ADP) in a small sample of 35 overweight (OW), 21 normal weight and 8 underweight volunteers. Waist and hip circumferences were assessed, and 15 of the OW subjects were measured before and after weight reduction.
Results: BIA and ADP provided similar cross-sectional estimates of group mean %FM (28.9 ± 10.0 and $31.3 \pm 13.0\%$, respectively). However, within individuals, there were large between-method differences ($\text{Diff}_{\text{BIA}-\text{ADP}}$) ranging from -13 to $+13$ %FM. Furthermore, we found a systematic bias of BIA related to the degree of adiposity. Consequently, %FM and fat mass loss during weight reduction in OW were underestimated with BIA when compared with ADP. Waist and hip circumferences were inversely associated with resistance (R) and reactance ($P < 0.01$), and with $\text{Diff}_{\text{BIA}-\text{ADP}}$ ($P < 0.001$). In women, the variability in hip circumference explained 76%, and in men, the variability in waist circumference explained 59% of $\text{Diff}_{\text{BIA}-\text{ADP}}$.
Conclusion: Resistance changes associated with variations in trunk circumferences decrease resistance, and therefore impair the accuracy of BIA to assess %FM.

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Keywords: body composition; fat mass; bioimpedance analysis; body shape

Introduction

Bioimpedance analysis (BIA) is widely applied to assess body composition in clinical practice and research settings. However, the European Society for Clinical Nutrition and Metabolism (ESPEN) guidelines question the accuracy of BIA at extreme body mass index (BMI) ranges and suggest that longitudinal follow-up data on body composition by BIA should be interpreted with caution (Kyle *et al*., 2004a). Correspondingly, BIA considerably underestimated total and truncal fat mass (Neovius *et al*., 2006) as well as fat mass loss in obese persons during weight reduction (Fogelholm *et al*., 1997). The reasons for the discrepant results are poorly understood. Therefore, the ESPEN guidelines suggest that further validation studies of BIA should be performed to clarify the issue. BIA is based on several assumptions that could lead to inaccurate results. First, the hydration of human soft tissue is not constant. The hydration state is significantly altered in overweight (OW) subjects (Waki *et al*., 1991; Haroun *et al*., 2005). Second, the measured body is not of cylindrical geometry. Large variations exist in cross-sectional areas of human bodies that are likely to be responsible for the lack of portability of BIA equations from one population to another (Kyle *et al*., 2004a). In an increasingly OW population, variations in body shape might significantly influence BIA accuracy. However, the effect of variations in truncal circumferences on whole-body impedance and thus the accuracy of BIA to determine percent fat mass (%FM) in a healthy population with varying nutritional status has never been quantified systematically. We reasoned that BIA underestimates %FM and underestimates fat mass

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loss achieved during weight reduction in obese persons, compared with air-displacement plethysmography (ADP). In addition, we hypothesized that trunk circumference variation affects impedance and could partly explain the different results in %FM obtained with BIA and ADP.

Subjects and methods

The ethical committee of the Charité approved the study, and written, informed consent was obtained from all participants. We enrolled 35 OW (BMI $\geqslant 25\,kg/m^2$), 21 normal weight (NW; BMI between 19.0 and $25.0\,kg/m^2$) and 8 underweight (UW; BMI $<18.5\,kg/m^2$, without clinical signs of edema) volunteers into this study. We recruited NW volunteers among university staff, and UW subjects from the Department of Psychosomatic Medicine during their inpatient treatment of eating disorders. In addition, we recruited OW subjects at the start of a 6-months weight reduction program, and 15 of these OW volunteers were retested after weight reduction. We carried out all tests in our Clinical Research Center in the morning after 12 h (OW and NW) or 2 h (UW) of fasting. Body height was assessed with a laser stadiometer (Soehnle, Leifheit AG, Nassau, Germany), and body circumferences with a non-stretchable measuring tape at standardized reference points (waist: half way between lower rib and iliac crest; hip: at the level of trochanter major). After resting for 10 min and voiding, BIA measurements (Helios, Forana, Forschung und Analyse GmbH, Frankfurt am Main, Germany) were carried out in the supine position. The subjects were carefully placed into a position suitable for BIA measurements, assuring separate placement of legs in an angle of about 30° in order to avoid overestimation of the trunk length, specifically in the OW. After cleaning the skin with disinfectant, we placed single-use electrodes (BIA Classic Tabs, MediCal Healthcare GmbH, Karlsruhe, Germany) on the dorsal surface of hand and foot of the dominant side, according to manufacturer instructions. Whole-body impedance was measured at 50 kHz and %FM was calculated according to an equation previously published by Sun *et al.* (2003) which was developed using a multi-compartment model (isotope dilution, densitometry and dual-energy X-ray absorptiometry) as the reference method. In this study, 1095 healthy male and female subjects aged 12–94 with a broad range of BMI (23.6 ± 5.6 to 30.0 ± 7.2) had been included. The s.e. of estimate when predicting fat mass with BIA has been shown to be between 1.9 and 3.6 kg (Kyle *et al.*, 2004b). Percent fat mass assessed with BIA and predicted according to Sun *et al.* will be referred to as %FM BIA_{SUN}. ADP was carried out immediately after BIA testing by using the BodPod (Life Measurement Inc., Concord, CA, USA). After a 30 min run-in phase, the BodPod was calibrated using a 50 l cylinder. Body weight was measured with the scale attached to the BodPod, which was calibrated daily. Then, body volume was measured after adjustments for predicted thoracic lung volume and estimated surface area artifact. Participants were dressed in tight underwear and wore a swim cap during the measurement. Fat mass was calculated according to the equation using the software provided by the manufacturer. Body volume was measured in duplicate or triplicate when the initial two measures differed by >150 ml.

Statistical analysis

We applied SPSS (version 18.0; SPSS Inc., Cary, NC, USA) for statistical analysis. Data are given as mean ± s.d. Between-group comparison was carried out with one-way analysis of variance followed by 2-tailed *post-hoc* Dunnett *t*-tests. We applied the paired *t*-test for intra-individual comparisons with $P<0.05$ considered as statistically significant. Bland–Altman analysis of agreement was carried out for method comparison (Bland, 1986). To identify parameters that explain the measurement difference between BIA and ADP, we carried out a stepwise regression analysis with the measurement difference ($Diff_{BIA-ADP}$) as dependent, and with gender, body weight, age, BMI, waist and hip circumference as independent variables.

Results

Hypothesis 1: the difference between BIA and ADP

Demographic subject characteristics and body composition of the study participants are shown in Table 1. The mean %FM was 28.9 ± 10.0 based on BIA_{SUN}, which was slightly but not significantly different from %FM as assessed with ADP (31.3 ± 13.0). However, Bland–Altman analysis showed wide limits of agreement, and maximum individual differences between BIA_{SUN} and ADP ranged from −13 to +13 %FM (Figure 1). The difference between %FM determined by ADP and BIA_{SUN} was inversely associated with mean %FM ($r=-0.57$, $P<0.001$). This finding indicated a systematic bias in the estimation of body fat according to BIA_{SUN}, which was related to the nutritional status of the subject, and lead to an overestimation of %FM in lean, as well as an underestimation of %FM in OW subjects. When estimates of %FM were compared within the three study groups separately, BIA_{SUN} significantly underestimated %FM in the OW group ($P<0.05$) while in the NW and UW group %FM determined by BIA_{SUN} and ADP gave similar results (Table 1). After the weight loss program, the OW participants had lost an average of 6.6 ± 2.7 kg body weight (range: 0.9–10.4 kg). ADP indicated a reduction in fat mass of 6.4 ± 2.6 kg in the OW group while BIA_{SUN} indicated a loss of only 3.7 ± 2.1 kg. This result was significantly less in comparison with ADP ($P<0.01$). When compared with ADP, individual difference with BIA_{SUN} ranged from underestimating fat mass loss by 7.4 kg to overestimating fat mass loss by 1.9 kg.

Hypothesis 2: variation in trunk circumference is responsible for the systematic difference between BIA and ADP

In the entire 64 participants study group, waist and hip circumferences were consistently and inversely correlated

Table 1 General characteristics, bioimpedance and body composition of OW, NW and UW subjects, as well as of the subgroup of overweight subjects before and after weight reduction

n *(m/f)*	*OW (9/26)*	*NW (7/14)*	*UW (0/8)*	*OW T0 (0/15)*	*OW T1 (0/15)*
Age (years)	41 ± 10 (25–61)*	34 ± 8 (23–54)	27 ± 11 (19–47)	40 ± 11 (28–61)	41 ± 11 (28–61)
Height (m)	1.69 ± 0.10 (1.54–1.88)*	1.76 ± 0.09 (1.62–1.94)	1.65 ± 0.05 (1.60–1.73)**	1.67 ± 0.07 (1.54–1.80)	1.67 ± 0.07 (1.54–1.80)
Weight (kg)	90.5 ± 15.3 (61.2–135.2)***	67.3 ± 10.6 (55.3–98.4)	45.3 ± 6.3 (38.4–55.0)***	91.6 ± 11.5 (75.2–110.5)	85.1 ± 10.6 (71.1–101.3)***
BMI (kg/m^2)	31.5 ± 4.1 (25.1–41.3)***	21.6 ± 1.7 (19–25)	16.6 ± 1.8 (14.0–18.6)**	32.7 ± 3.0 (28.2–61.0)	30.4 ± 2.7 (26.1–34.5)***
Waist (cm)	98 ± 12 (75–124)***	76 ± 8 (56–91)	65 ± 5 (57–72)*	99 ± 10 (77–120)	95 ± 9 (76–110)***
Hip (cm)	112 ± 9 (92–126)***	94 ± 5 (84–103)	77 ± 7 (71–92)***	116 ± 7 (105–126)	114 ± 6 (103–125)
R (ohm)	489 ± 64 (331–606)***	604 ± 75 (479–717)	732 ± 51 (686–851)***	501 ± 52 (405–603)	539 ± 64 (419–649)**
Xc (ohm)	50 ± 7 (33–67)***	58 ± 9 (46–75)	56 ± 8 (45–71)	48 ± 6 (38–59)	52 ± 4 (47–60)***
FM_{ADP} (kg)	36.5 ± 11.1 (8.6–56.3)***	15.0 ± 3.2 (9.5–19.4)	7.0 ± 3.8 (0.8–13.6)*	41.7 ± 7.1 (30.4–53.1)	35.3 ± 6.4 (25.3–43.9)***
FM_{ADP} (%)	40.1 ± 9.7 (10.7–54.3)***	22.9 ± 6.1 (10.9–31.7)	14.9 ± 6.6 (2.1–25.7)*	45.4 ± 3.7 (40.5–54.3)	41.4 ± 3.9 (34.5–49.4)***
FM_{BIA_SUN} (kg)	31.9 ± 8.1 (16.8–45.6)***	15.9 ± 2.3 (10.5–19.1)	6.6 ± 4.2 (0.4–12.1)**	36.5 ± 5.8 (25.6–45.6)	32.9 ± 5.4 (22.3–42.7)***
FM_{BIA_SUN} (%)	38.6 ± 6.2 (20.3–46.2)***	23.9 ± 3.7 (17.8–28.8)	13.8 ± 7.6 (0.9–22.0)**	39.8 ± 2.7 (34.0–43.5)	38.6 ± 3.3 (31.1–43.6)*

Abbreviations: BMI, body mass index; f, female; FM, fat mass; FM_{ADP}, FM measured with air-displacement plethysmography, $FM_{BIA\ SUN}$, FM measured with bioelectrical impedance and predicted according to Sun *et al.*; m, male; NW, normal weight; OW, overweight; R, resistance; UW, underweight; Xc, reactance.
***$P<0.001$; **$P<0.01$; *$P<0.05$ when comparing OW and UW with NW, and OW T0 with OW T1.

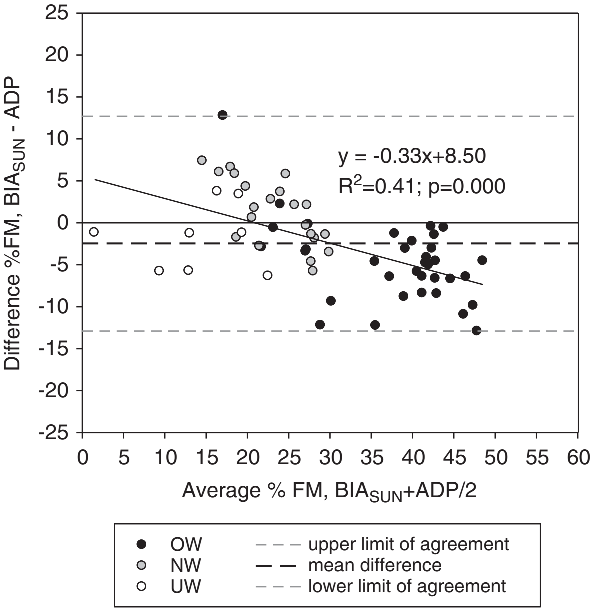

Figure 1 Bland–Altman plot for analyzing the agreement between BIA_{SUN} and ADP for assessing percent body fat in OW, NW and UW subjects.

with resistance (R_{50}; waist $r=-0.54$, $P<0.01$; hip $r=-0.47$, $P<0.01$), reactance (Xc_{50}; waist $r=-0.47$, $P<0.01$; hip $r=-0.50$, $P<0.01$) as well as with the measurement difference between BIA and ADP ($Diff_{BIA-ADP}$; Figure 2). To assess whether or not individual variability in truncal circumferences independently affected $Diff_{BIA-ADP}$, we performed a stepwise regression analysis with $Diff_{BIA-ADP}$ as dependent, and with gender, age, body weight, BMI and truncal circumferences as independent variables. Gender ($P=0.007$), BMI ($P=0.039$) and hip circumference ($P=0.062$) entered the model as independent predictors and together explained 70% of the measurement difference.

Although based on a relatively small sample size, we aimed at further exploring the role of gender differences in the variance of measurement differences, and repeated the stepwise regression analysis for women ($n=48$) and men ($n=16$) separately. In women, hip circumference was the single significant predictor explaining 76% of the variance of the measurement difference. In contrast, in males, the single significant predictor was waist circumference explaining 57% of the observed variance. The results of the regression analysis are shown in Table 2.

Discussion

The equation of Sun *et al.* to predict fat mass performed relatively well to estimate group average fat mass in the normal and UW subjects, but led to an underestimation in the OW group (Table 1). Similar findings have been documented earlier (Deurenberg, 1996; Bosy-Westphal *et al.*, 2008), and led to the development of obese-specific equations. BIA underestimates fat mass loss in obese women during weight reduction by −2.8 to +1.6 when compared with dual-energy X-ray absorptiometry (Webber *et al.*, 1994) or with a criterion 4C model (Fogelholm *et al.*, 1997). While showing the same trend, our results comparing BIA with ADP suggested a more pronounced absolute bias (Table 1, Figure 1).

We extrapolated the extremes of the bias derived from the cross-sectional part of our study in the OW group to a longitudinal 'worst case' scenario, and found that FM could be under- and overestimated by 13% both before and at the end of a weight reduction program by BIA_{SUN}. In a given subject with a loss of 24% FM according to ADP (that is, from 49 to 25%), BIA_{SUN} could thus estimate a gain of 2% FM (36 to 48%). On average, the difference between ADP and BIA_{FOR} can be expected to be much less extreme. In our study, ADP

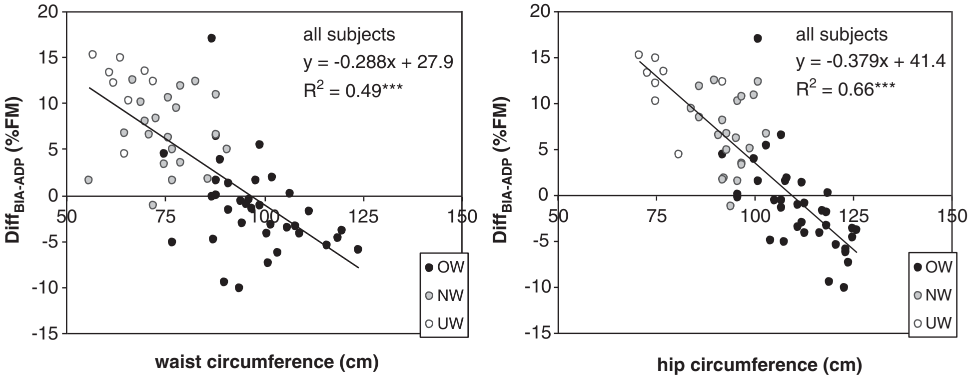

Figure 2 Association of truncal circumferences with the measurement difference of %FM between BIA and ADP ($Diff_{BIA-ADP}$).

Table 2 Effect of variation in truncal circumferences (waist and hip) on the measured difference between BIA and ADP: multiple stepwise regression analysis

Independent variable	*β*	P	*Adj. R^2*
Model 1	All subjects (*n* = *64*)		0.702
Gender	0.194	0.007	
BMI	−0.444	0.039	
Hip	−0.400	0.062	
Model 2	Women (*n* = *48*)		0.764
Hip	−0.877	0.000	
Model 3	Men (*n* = *16*)		0.594
Waist	−0.771	0.000	

Abbreviations: Adj., adjusted; ADP, air-displacement plethysmography; BIA, bioelectrical impedance analysis; Hip, hip circumference (cm); Waist, waist circumference (cm).

estimated a fat mass loss from 45.4 to 41.4% (−4%) and BIA_{SUN} from 39.8 to 38.5% (−1.3%). Still this difference should not be neglected. We do not know if more pronounced weight loss would lead to an even greater discrepancy.

Our findings imply that fat mass of OW subjects and the success of weight reduction programs in terms of fat mass reduction will be underestimated with BIA_{SUN}. The idea that BIA accuracy depends on the choice of an adequate population-specific prediction equation (Kyle *et al.*, 2004a) is well accepted in obese people. However, how could BIA be applied to a group of people with heterogeneous nutritional status, or to subjects undergoing transition from an OW to a NW state? We suggest that, instead of accumulating an increasing amount of population-specific BIA equations, a better understanding of the strengths and weaknesses of the BIA technique could be more beneficial.

The physical principle behind BIA is that resistance (R) of a homogeneous conductive material of uniform cross-sectional area is proportional to its length (L) and inversely proportional to its cross-sectional area. Although the body is not a uniform cylinder and its conductivity is not constant, an empirical relationship can be established between the impedance quotient (L^2/R) and the volume of water, which contains electrolytes that conduct the electrical current through the body (Kyle *et al.*, 2004b). According to previous studies (Hoffer *et al.*, 1969; Lukaski *et al.*, 1985), correlations between impedance and total body water are uniformly high suggesting that the theory behind this measurement is valid. However, one of the assumptions behind impedance measurements clearly relates to a uniform geometry of the measured body, which apparently is not the case with a human body.

The extremities account for 91% of whole-body R while the contribution of the trunk was only $<10\%$ (Zhu *et al.*, 1998). Despite the small contribution of the trunk to whole-body impedance, we found that truncal circumferences were consistently and inversely associated with whole-body impedance. In addition, we were able to demonstrate that individual variation in hip circumference in women, and waist circumference in men explained a major part of the observed difference between ADP and BIA, independent of variations in weight or BMI. We are aware that our study is small, and suggest that our findings should be interpreted with caution. Future studies with larger sample sizes of mixed gender are needed to characterize the effect of variations in body shape on body impedance in better detail. Nonetheless, we believe that our data provide clear indicators of what parameters should be studied and what results could be expected.

Conclusions

Our study provides specific insight into the limitations of BIA to accurately predict fat mass in a heterogeneous group and in OW subjects during weight loss. In addition, our study also identified gender-specific variations in central body shape as one of the major underlying reasons causing the different results on %FM between BIA and ADP. In future studies, the accuracy of BIA could be improved by adjusting measured resistance for the subject's trunk circumference.

Study limitations

We used a comparison with ADP and not a 4C model to assess body fat. In addition, we predicted lung volume in the OW subjects rather than measuring this parameter directly. These issues could have introduced a systematic measurement bias in our study.

Conflict of interest

The authors declare no conflict of interest.

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