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

3  
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7  
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31  
32 **Running title:** Body shape and bioimpedance analysis

33

34 **ABSTRACT**

35 **Objective:** To test the hypothesis that variations in trunk circumferences  
36 influence the accuracy of bioimpedance analysis (BIA) for assessment of  
37 percent fat mass (%FM).

38 **Subjects and methods:** %FM was predicted with BIA and compared with air-  
39 displacement plethysmography (ADP) in a small sample of 35 overweight (OW),  
40 21 normal weight (NW), and 8 underweight (UW) volunteers. Waist and hip  
41 circumferences were assessed, and 15 of the OW subjects were measured  
42 before and after weight reduction.

43 **Results:** BIA and ADP provided similar cross-sectional estimates of group  
44 mean %FM ( $28.9 \pm 10.0$  and  $31.3 \pm 13.0\%$ , respectively). However within  
45 individuals, there were large between-method differences ( $\text{Diff}_{\text{BIA-ADP}}$ ) ranging  
46 from -13 to +13 %FM. Furthermore, we found a systematic bias of BIA related  
47 to the degree of adiposity. Consequently, %FM and fat mass loss during weight  
48 reduction in OW were underestimated with BIA when compared with ADP.  
49 Waist and hip circumference were inversely associated with resistance and  
50 reactance ( $p < 0.01$ ), and with  $\text{Diff}_{\text{BIA-ADP}}$  ( $p < 0.001$ ). In women, the variability in  
51 hip circumference explained 76%, and in men variability in waist circumference  
52 explained 59% of  $\text{Diff}_{\text{BIA-ADP}}$ .

53 **Conclusion:** Resistance changes associated with variations in trunk  
54 circumferences decrease resistance and therefore impair the accuracy of BIA to  
55 assess %FM.

56

57 **Key words:** body composition – fat mass - bioimpedance analysis – body  
58 shape

59

## 60 **Introduction**

61 Bioimpedance analysis (BIA) is widely applied to assess body  
62 composition in clinical practice and research settings. However the European  
63 Society for Clinical Nutrition and Metabolism (ESPEN) guidelines question the  
64 accuracy of BIA at extreme BMI ranges and suggest that longitudinal follow-up  
65 data on body composition by BIA should be interpreted with caution (Kyle et al.,  
66 2004b). Correspondingly BIA considerably underestimated total and truncal fat  
67 mass (Neovius et al., 2006) as well as fat mass loss in obese persons during  
68 weight reduction (Fogelholm et al., 1997). The reasons for the discrepant  
69 results are poorly understood. Therefore, the ESPEN guidelines suggest that  
70 further validation studies of BIA should be performed to clarify the issue. BIA is  
71 based on several assumptions that could lead to inaccurate results. First, the  
72 hydration of human soft tissue is not constant. The hydration state is  
73 significantly altered in overweight subjects (Haroun et al., 2005;Waki et al.,  
74 1991). Second, the measured body is not of cylindrical geometry. Large  
75 variations exist in cross-sectional areas of human bodies that are likely to be  
76 responsible for the lack of portability of BIA equations from one population to  
77 another (Kyle et al., 2004b). In an increasingly overweight population, variations  
78 in body shape might significantly influence BIA accuracy. However the effect of  
79 variations in truncal circumferences on whole body impedance and thus the  
80 accuracy of BIA to determine percent fat mass (%FM) in a healthy population  
81 with varying nutritional status has never been quantified systematically. We  
82 reasoned that BIA underestimates %FM and underestimates fat mass loss  
83 achieved during weight reduction, in obese persons compared with ADP. In  
84 addition, we hypothesized that trunk circumference variation affects impedance

85 and could partly explain the different results in %FM obtained with BIA and  
86 ADP.

87

## 88 **Subjects and methods**

89           The ethical committee of the Charité approved the study and written,  
90 informed consent was obtained from all participants. We enrolled 35 overweight  
91 (OW; BMI  $\geq$  25 kg/m<sup>2</sup>), 21 normal weight (NW; BMI between 19.0 and 25.0  
92 kg/m<sup>2</sup>) and 8 underweight (UW; BMI < 18.5 kg/m<sup>2</sup>, without clinical signs of  
93 edema) volunteers into this study. We recruited NW volunteers among  
94 university staff, and UW subjects from the Department of Psychosomatic  
95 Medicine during their inpatient treatment of eating disorders. In addition we  
96 recruited OW subjects at the start of a 6-months weight reduction program, and  
97 fifteen of these OW volunteers were retested after weight reduction. We carried  
98 out all tests in our Clinical Research Center in the morning after a 12 hours (OW  
99 and NW) or 2 hours (UW) of fasting. Body height was assessed with a laser  
100 stadiometer (Soehnle Leifheit AG, Germany), and body circumferences with a  
101 non-stretchable measuring tape at standardized reference points (waist: half  
102 way between lower rib and iliac crest; hip: at the level of trochanter major). After  
103 resting for 10 minutes and voiding, BIA measurements (Helios, Forana,  
104 Forschung und Analyse GmbH, Frankfurt am Main, Germany) were carried out  
105 in the supine position. The subjects were carefully placed into a position  
106 suitable for BIA measurements, assuring separate placement of legs in an  
107 angle of about 30 degrees in order to avoid overestimation of the trunk length,  
108 specifically in the OW. After cleaning the skin with disinfectant, we placed  
109 single-use electrodes (BIA Classic Tabs, MediCal Healthcare GmbH, Karlsruhe,  
110 Germany) on the dorsal surface of hand and foot of the dominant side,  
111 according to manufacturer instructions. Whole body impedance was measured  
112 at 50 kHz analysis and %FM was calculated according to an equation  
113 previously published by Sun et al. (%FM<sub>BIA\_SUN</sub>) which was developed using a

114 multi-compartment model (isotope dilution, densitometry and Dual-Energy X-  
115 Ray absorptiometry) as the reference method (Sun et al., 2003). In this study,  
116 1095 healthy male and female subjects aged 12 – 94 with a broad range of BMI  
117 ( $23.6 \pm 5.6$  to  $30.0 \pm 7.2$ ) had been included. The standard error of estimate  
118 when predicting fat mass with BIA has been shown to be between 1.9 and 3.6  
119 kg (Kyle et al., 2004a). ADP was carried out immediately after BIA testing by  
120 using the BodPod<sup>®</sup> (Life Measurement Inc. Concord, CA, U.S.A). After a 30 min  
121 run-in phase, the BodPod was calibrated using a 50 l cylinder. Body weight was  
122 measured with the scale attached to the BodPod which was calibrated daily.  
123 Then, body volume was measured after adjustments for predicted thoracic lung  
124 volume and estimated surface area artifact. Participants were dressed in tight  
125 underwear and wore a swim cap during the measurement. Fat mass was  
126 calculated according to the equation by Siri using the software provided by the  
127 manufacturer. Body volume was measured in duplicate or triplicate when the  
128 initial two measures differed by >150 ml

129

### 130 Statistical analysis

131 We applied SPSS (version 18.0; SPSS Inc. Cary., NC) for statistical  
132 analysis. Data are given as mean  $\pm$  SD. Between-group comparison was  
133 carried out with one-way ANOVA followed by 2-tailed post-hoc Dunnett t-tests.  
134 We applied the paired t-test for intra-individual comparisons with  $p < 0.05$   
135 considered as statistically significant. Bland & Altman analysis of agreement  
136 was carried out for method comparison (Bland, 1986). To identify parameters  
137 that explain the measurement difference between BIA and ADP, we carried out  
138 a stepwise regression analysis with the measurement difference ( $\text{Diff}_{\text{BIA-ADP}}$ ) as

139 dependent, and with gender, body weight, age, BMI, waist and hip  
140 circumference as independent variables.

141



142 **Results**

143 *Hypothesis 1: the difference between BIA and ADP*

144 Demographic subject characteristics and body composition of the study  
145 participants are shown in Table 1. The mean %FM was  $28.9 \pm 10.0$  based on  
146  $BIA_{SUN}$ , which was slightly but not significantly different from %FM as assessed  
147 with ADP ( $31.3 \pm 13.0$ ). However Bland & Altman Analysis of agreement  
148 showed wide limits of agreement, and maximum individual differences between  
149  $BIA_{SUN}$  and ADP ranged from -13 to +13 %FM (Fig.1). The difference between  
150 %FM determined by ADP and  $BIA_{SUN}$  was inversely associated with mean %FM  
151 ( $r = -0.57$ ,  $p < 0.001$ ). This finding indicated a systematic bias in the estimation  
152 of body fat according to  $BIA_{SUN}$  which was related to the nutritional status of the  
153 subject, and lead to an overestimation of %FM in lean, as well as an  
154 underestimation of %FM in overweight subjects. When estimates of percent  
155 %FM were compared within the three study groups separately,  $BIA_{SUN}$   
156 significantly underestimated %FM in the OW group ( $p < 0.05$ ) while in the NW  
157 and UW group %FM determined by  $BIA_{SUN}$  and ADP gave similar results (Table  
158 1). After the weight loss program, the OW participants had lost an average of  
159  $6.6 \pm 2.7$  kg (range: 0.9 – 10.4 kg). ADP indicated a reduction in fat mass of  $6.4$   
160  $\pm 2.6$  kg in the OW group while  $BIA_{SUN}$  indicated a loss of only  $3.7 \pm 2.1$  kg. This  
161 result was significantly less in comparison with ADP ( $p < 0.01$ ). When compared  
162 with ADP, individual difference with  $BIA_{SUN}$  ranged from underestimating fat  
163 mass loss by 7.4 kg to overestimating fat mass loss by 1.9 kg.

164

165 *Hypothesis 2: Variation in trunk circumference is responsible for the systematic*  
166 *difference between BIA and ADP*

167 In the entire 64 participants study group, waist and hip circumference  
168 were consistently and inversely correlated with resistance ( $R_{50}$ ; waist  $r = -0.54$ ,  
169  $p < 0.01$ ; hip  $r = -0.47$ ;  $p < 0.01$ ), reactance ( $X_{C50}$ ; waist  $r = -0.47$ ,  $p < 0.01$ ; hip  $r$   
170  $= -0.50$ ;  $p < 0.01$ ) as well as with the measurement difference between BIA and  
171 ADP ( $\text{Diff}_{\text{BIA-ADP}}$ ; Figure 2). To assess whether or not individual variability in  
172 truncal circumferences independently affected  $\text{Diff}_{\text{BIA-ADP}}$ , we performed a  
173 stepwise regression analysis with  $\text{Diff}_{\text{BIA-ADP}}$  as dependent, and with gender,  
174 age, body weight, BMI and truncal circumferences as independent variables.  
175 Gender ( $p = 0.007$ ), BMI ( $p = 0.039$ ) and hip circumference ( $p = 0.062$ ) entered  
176 the model as independent predictors and together explained 70% of the  
177 measurement difference. Although based on a relatively small sample size, we  
178 aimed at further exploring the role of gender differences in the variance of  
179 measurement differences, and repeated the stepwise regression analysis for  
180 women ( $n = 48$ ) and men ( $n = 16$ ) separately. In women, hip circumference was  
181 the single significant predictor explaining 76% of the variance of the  
182 measurement difference. In contrast in males, the single significant predictor  
183 was waist circumference, explaining 57% of the observed variance. The results  
184 of the regression analysis are shown in table 2.

185

## 186 **Discussion**

187         The equation of Sun et al. to predict fat mass performed relatively well to  
188 estimate group average fat mass in the normal- and underweight subjects, but  
189 led to an underestimation in the overweight group (table 1). Similar findings  
190 have been documented earlier (Deurenberg, 1996; Bosy-Westphal et al., 2008)  
191 and led to the development of obese-specific equations. BIA underestimates fat  
192 mass loss in obese women during weight reduction by -2.8 to +1.6 when  
193 compared with dual-energy X-Ray absorptiometry (DEXA) (Webber et al., 1994)  
194 or with a criterion 4C model (Fogelholm et al., 1997). While showing the same  
195 trend, our results comparing BIA with ADP suggested a more pronounced  
196 absolute bias (table 1, figure 1).

197         We extrapolated the extremes of the bias derived from the cross-  
198 sectional part of our study in the OW group to a longitudinal “worst case”  
199 scenario, and found that FM could be under- and overestimated by 13% both  
200 before and at the end of a weight reduction program by  $BIA_{SUN}$ . In a given  
201 subject with a loss of 24% FM according to ADP (i.e. from 49 to 25%),  $BIA_{SUN}$   
202 could thus estimate a gain of 2% FM (36 to 48%). On average, the difference  
203 between ADP and  $BIA_{FOR}$  can be expected to be much less extreme. In our  
204 study, ADP estimated a fat mass loss from 45.4 to 41.4 % (- 4%), and  $BIA_{SUN}$   
205 from 39.8 to 38.5 % (= - 1.3%). Still this difference should not be neglected. We  
206 do not know if more pronounced weight loss would lead to an even greater  
207 discrepancy.

208         Our findings imply that fat mass of overweight subjects, and the success  
209 of weight reduction programs in terms of fat mass reduction, will be  
210 underestimated with  $BIA_{SUN}$ . The idea that BIA accuracy depends on the choice  
211 of an adequate population-specific prediction equation (Kyle et al., 2004b) is

212 well accepted obese people. However, how could BIA be applied to a group of  
213 people with heterogeneous nutritional status, or to subjects undergoing  
214 transition from an overweight to a normal weight state? We suggest that instead  
215 of accumulating an increasing amount of population-specific BIA equations, a  
216 better understanding of the strengths and weaknesses of the BIA technique  
217 could be more beneficial.

218

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

231         The extremities account for 91% of whole body resistance while the  
232 contribution of the trunk was only < 10% (Zhu et al., 1998). Despite the small  
233 contribution of the trunk to whole body impedance, we found that truncal  
234 circumferences were consistently and inversely associated with whole body  
235 impedance. In addition, we were able to demonstrate that individual variation in  
236 hip circumference in women, and waist circumference in men, explained a  
237 major part of the observed difference between ADP and BIA, independent of

238 variations in weight or BMI. We are aware that our study is small and suggest  
239 that our findings should be interpreted with caution. Future studies with larger  
240 sample sizes of mixed gender are needed to characterize the effect of  
241 variations in body shape on body impedance in better detail. Nonetheless, we  
242 believe that our data provide clear indicators of what parameters should be  
243 studied, and what results could be expected.

244

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246 support during the weight reduction program.

247

248 **Conflict of interest:** we are not aware of interest conflicts.

#### 249 **Study limitations**

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

254

#### 255 **Conclusions and outlook**

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

263

264

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322



323 **Table 1.** General characteristics, bioimpedance, and body composition of overweight  
 324 (OW), normal weight (NW) and underweight (UW) subjects, as well as of the subgroup  
 325 of overweight subjects before and after weight reduction.  
 326

n (m/f)	OW (9/26)	NW (7/14)	UW (0/8)	OW T0 (0/15)	OW T1 (0/15)
<b>age (y)</b>	41 ± 10* (25 – 61)	34 ± 8 (23 – 54)	27 ± 11 (19 – 47)	40 ± 11 (28 – 61)	41 ± 11 (28 – 61)
<b>height (m)</b>	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)
<b>weight (kg)</b>	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)
<b>BMI (kg/m<sup>2</sup>)</b>	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)
<b>waist (cm)</b>	98 ± 12*** (75 – 124)	76 ± 8 (56 – 91)	65 ± 5 (57 – 72)	99 ± 10 (77 – 120)	95 ± 9*** (76 – 110)
<b>hip (cm)</b>	112 ± 9*** (92 – 126)	94 ± 5 (84 – 103)	77 ± 7 (71 – 92)	116 ± 7 (105 – 126)	114 ± 6 (103 – 125)
<b>R (ohm)</b>	489 ± 64*** (331 – 606)	604 ± 75 (479 – 717)	732 ± 51 (686 – 851)	501 ± 52 (405 – 603)	539 ± 64** (419 – 649)
<b>Xc (ohm)</b>	50 ± 7*** (33 – 67)	58 ± 9 (46 – 75)	56 ± 8 (45 – 71)	48 ± 6 (38 – 59)	52 ± 4*** (47 – 60)
<b>FM<sub>ADP</sub> (kg)</b>	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)
<b>FM<sub>ADP</sub> (%)</b>	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)
<b>FM<sub>BIA SUN</sub> (kg)</b>	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)
<b>FM<sub>BIA SUN</sub> (%)</b>	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)

BMI, Body Mass Index; R, Resistance; Xc, Reactance; 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. \*\*\*, p < 0.001; \*\*, p < 0.01; \*, p < 0.05 when comparing OW and UW with NW, and OW T0 with OW T1;

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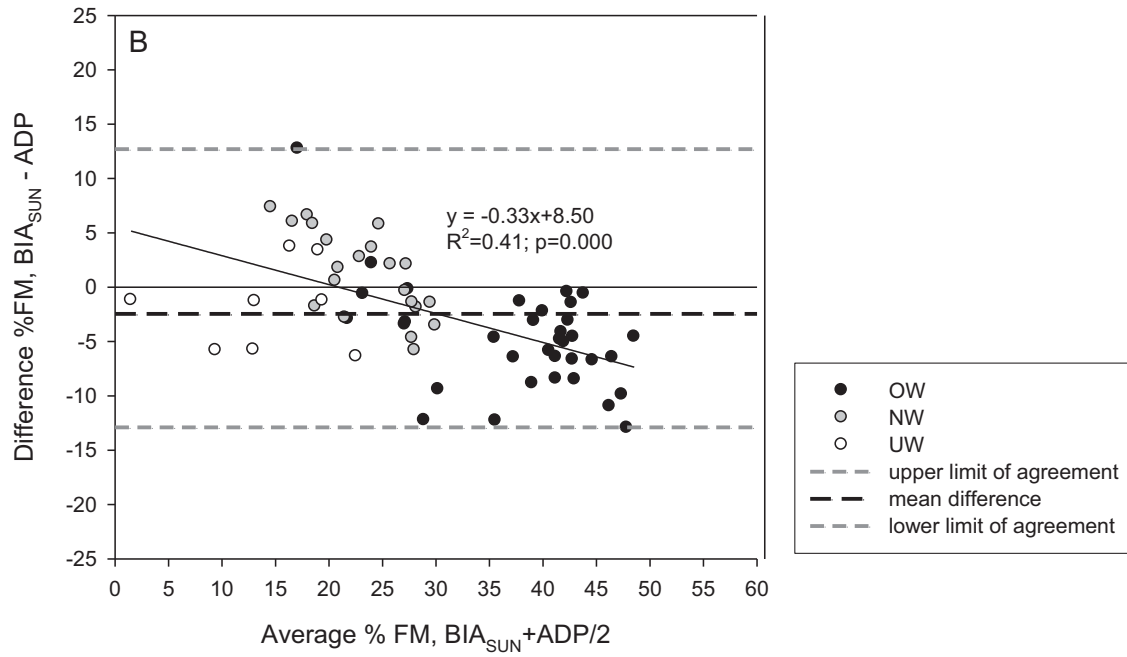
**Table 2.** Effect of variation in truncal circumferences (waist, hip) on the measured  
 difference between bioelectrical impedance analysis (BIA) and air-displacement  
 plethysmography (ADP): multiple stepwise regression analysis.

independent variable	$\beta$	P	adj. R <sup>2</sup>
Model 1	<i>all subjects (n=64)</i>		0.702
Gender		0.194	0.007
BMI		-0.444	0.039
Hip		-0.400	0.062
Model 2	<i>Women (n = 48)</i>		0.764
Hip		-0.877	0.000
Model 3	<i>Men (n = 16)</i>		0.594
Waist		-0.771	0.000

Waist, waist circumference (cm); Hip, hip circumference (cm)

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**Figure 1.** Bland & Altman plot for analyzing the agreement between BIA<sub>SUN</sub> and ADP for assessing percent body fat in overweight (OW), normal weight (NW) and underweight (UW) subjects.



**Figure 2:** Association of truncal circumferences with the measurement difference of %FM between BIA and ADP ( $\text{Diff}_{\text{BIA-ADP}}$ ).

