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ORIGINAL COMMUNICATION

Accuracy of eight-polar bioelectrical impedance analysis for the assessment of total and appendicular body composition in peritoneal dialysis patients

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Objective: To establish the accuracy of bioelectrical impedance analysis (BIA) for the assessment of total and appendicular body composition in peritoneal dialysis (PD) patients.
Design: Cross-sectional study.
Setting: University Nephrology Clinic.
Subjects: In all, 20 PD patients and 77 healthy controls matched for gender, age and body mass index.
Methods: Whole-body fat-free mass (FFM) and appendicular lean tissue mass (LTM) were measured by dual-energy X-ray absorptiometry. Resistance (*R*) of arms, trunk and legs was measured by eight-polar BIA at frequencies of 5, 50, 250 and 500 kHz. Whole-body resistance was calculated as the sum of *R* of arms, trunk and legs. The resistance index (RI) was calculated as the ratio between squared height and whole-body or segmental *R*.
Results: RI at 500 kHz was the best predictor of FFM, LTM_{arm} and LTM_{leg} in both PD patients and controls. Equations developed on controls overestimated FFM and LTM_{arm} and underestimated LTM_{leg} when applied to PD patients. Specific equations were thus developed for PD patients. Using these equations, the percent root mean-squared errors of the estimate for PD patients *vs* controls were 5 *vs* 6% for FFM, 8 *vs* 8% for LTM_{arm} and 7 *vs* 8% for LTM_{leg}.
Conclusion: Eight-polar BIA offers accurate estimates of total and appendicular body composition in PD patients, provided that population-specific equations are used.
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Introduction

The body composition of peritoneal dialysis (PD) patients may differ substantially from that of healthy individuals of the same age and gender. PD patients may have in fact a lower total body potassium, a lower total body nitrogen, and a lower or higher extra- to intracellular water ratio as compared to healthy individuals (Borovnicar *et al*, 1996; Woodrow *et al*, 1996a, 2001, 2004; Konings *et al*, 2003). These abnormalities render many body composition methods inadequate for the study of PD patients (Konings *et al*, 2003). An assessment of body composition is nonetheless important in PD patients because protein-energy malnutrition is a strong predictor of morbidity and mortality in dialysis patients (Kopple, 1997; Cano, 1999; Locatelli *et al*, 2002).

Dual-energy X-ray absorptiometry (DXA) is presently regarded as the most practical means of obtaining an accurate assessment of fat-free mass (FFM) and fat mass (FM) in dialysis patients (Locatelli *et al*, 2002). The

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***Guarantors*: G Medici and G Bedogni.**
***Contributions*: GM performed the selection and clinical evaluation of patients. CM performed dual-energy X-ray absorptiometry of patients and controls and BIA measurements of patients. ALF performed the nutritional and anthropometric assessment of patients and controls. MM performed the selection and BIA measurements of controls. AA coordinated the study. GB analyzed the data and wrote the paper.**
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three-compartment DXA model separates body mass into FM, lean tissue mass (LTM) and bone mineral content (BMC), with the sum of LTM and BMC representing FFM. At the appendicular level, LTM is synonym with muscle mass so that DXA provides also a means of evaluating arm and leg muscularity (Wang *et al*, 1999). Interestingly, clinically stable PD patients may have a lower appendicular LTM than healthy controls (Woodrow *et al*, 1996b). A major limitation of DXA is, however, that it cannot be employed outside of specialized centers because of technical and logistical constraints.

Bioelectrical impedance analysis (BIA) is a portable technique that has been crossvalidated against DXA for the assessment of FFM in PD patients (Bhatla *et al*, 1995; Woodrow *et al*, 1996b, 1997; Konings *et al*, 2002). In healthy subjects, segmental BIA has been shown to offer accurate estimates of appendicular body composition (Pietrobelli *et al*, 1998, 2004; Malavolti *et al*, 2003). However, segmental BIA has never been evaluated for the assessment of appendicular muscle mass in PD patients.

Eight-polar BIA is a recently introduced technique with three interesting characteristics: (1) the use of very practical tactile electrodes, (2) the absence of need to standardize subject's posture before BIA, and (3) the rapidity of measurement. We have shown that eight-polar BIA offers accurate estimates of total body water, extracellular water, FFM and appendicular LTM in healthy and obese subjects (Bedogni *et al*, 2002; Malavolti *et al*, 2003; Sartorio *et al*, 2005).

The present study aimed to establish the accuracy of eight-polar BIA for the assessment of whole-body FFM and appendicular LTM in PD patients.

Materials and methods

Subjects

In all, 20 patients with chronic kidney disease treated by continuous ambulatory PD were consecutively studied at the Peritoneal Dialysis Unit of the Nephrology Clinic of Modena and Reggio Emilia University (Modena, Italy). PD treatment had been started at a median of 119 (range: 58–684) days before the enrollment into the study. All patients were performing four cycles of PD every day, three during day and one at night, with a dextrose-based dialysis solution. A total of 77 healthy individuals matched for age, gender and BMI with PD patients, recruited among the personnel of the University, served as controls. All measurements were performed in the morning after an overnight fast ($\geq$8 h). PD patients were measured with the dialysis solution in the peritoneum, coherently with their treatment program. Fertile women were measured between the 6th and 10th day of the menstrual cycle. The study procedures had been approved by the local Ethical Committee and all subjects gave informed consent.

Anthropometry

All anthropometric measurements were performed by the same operator following the *Anthropometric Standardization Reference Manual* (Lohman *et al*, 1988). Weight (Wt) was measured to the nearest 0.01 kg and height (Ht) to the nearest 0.001 m. BMI was calculated as Wt (kg)/Ht $(m)^2$.

Eight-polar BIA

The resistance (R) of arms, trunk and legs was measured at frequencies of 5, 50, 250 and 500 kHz with an eight-polar tactile-electrode impedance meter (InBody 3.0, Biospace, Seoul, Korea). This instrument makes use of eight tactile electrodes: two are in contact with the palm (E1, E3) and thumb (E2, E4) of each hand and two with the anterior (E5, E7) and posterior aspects (E6, E8) of the sole of each foot (Figure 1).

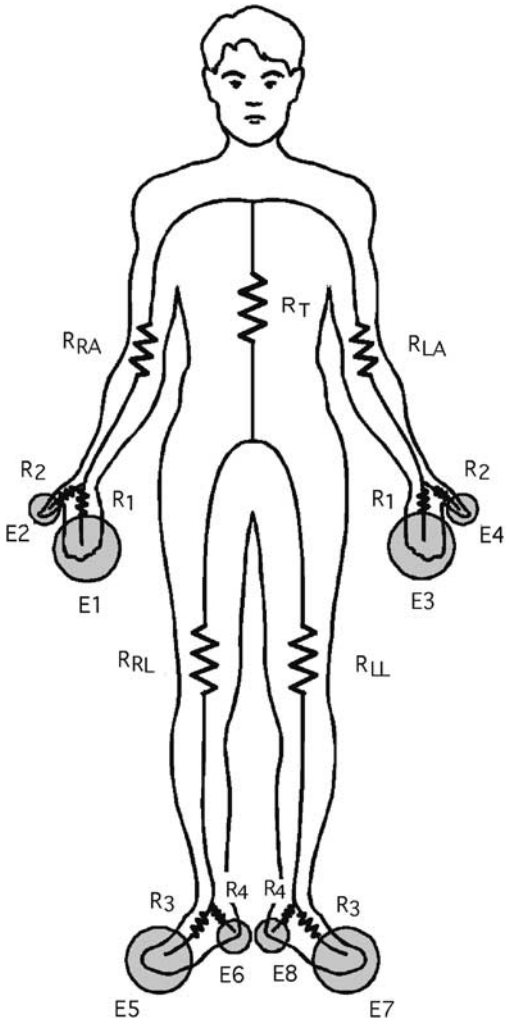

Figure 1 Current pathways of eight-polar BIA (graph reproduced with permission of Biospace). R_{RA} = resistance of right arm; R_T = resistance of trunk; R_{LA} = resistance of left arm; R_{RL} = resistance of right leg; R_{LL} = resistance of left leg.

The subject stands with her or his soles in contact with the foot electrodes and grabs the hand electrodes. The sequence of measurements, controlled by a microprocessor, proceeds as follows. An alternating current (a.c.) of 250 μA of intensity (I) is applied between E1 and E5. The recorded voltage difference (V) between E2 and E4 is divided for I to obtain the resistance of the right arm (R_{RA}). The same sequence is performed with V recorded between E4 and E8 to obtain trunk resistance (R_T) and with V recorded between E6 and E8 to obtain the resistance of the right leg (R_{RL}). The a.c. is then applied between E3 and E7 and the value of V measured between E2 and E4 is used to calculate the resistance of the left arm (R_{LA}). Lastly, the value of V measured between E6 and E8 is used to calculate the resistance of the left leg (R_{LL}). No caution was taken to standardize the posture of the subjects before BIA, as suggested by the manufacturer. Whole-body resistance at frequency x (R_{sumx}) was calculated as the sum of segmental R_x (right arm + left arm + trunk + right leg + left leg) (Bedogni *et al*, 2002). The whole-body resistance index (RI_{sumx}) was calculated as Ht $(cm)^2/R_{sumx}$ (Ω), the arm resistance index (RI_{armx}) as Ht $(cm)^2/R_{armx}$ (Ω) and the leg resistance index (RI_{legx}) as Ht $(cm)^2/R_{legx}$ (Ω) (Bedogni *et al*, 2002). Mean values of appendicular LTM and RI were used due to the absence of significant RI × hemisome interactions in the relationship between body composition and RI in both PD patients and controls (Malavolti *et al*, 2003). The within-day precision of InBody in three PD patients and five controls was ≤2.0%.

DXA

DXA scans were performed by the same operator using a Lunar DPX-L densitometer and adult software version 3.6 (Lunar Corporation, Madison, WI, USA). The precision of whole-body LTM and BMC assessment, as determined by three repeated weekly measurements on three healthy subjects, was 2.5 and 1.0%, respectively (Malavolti *et al*, 2003). In the same subjects, the precision of appendicular LTM assessment was ≤2.5% and that of FM was 2.0%. The difference between body mass measured by DXA and Wt measured by scale in the pooled sample was −1.0 ± 1.0 kg. In spite of its statistical significance ($P<0.0001$, Student's paired t-test), this difference is of no practical concern.

Statistical analysis

The number of PD patients to study was determined by considering that a sample size of 20 has a 100% power to detect a slope comprised between 1.0 and 2.0 when the standard deviation (s.d.) of X (RI_{sum500}) is 6 Ω, the correlation coefficient is 0.90 and the level of alpha is 0.05 (Malavolti *et al*, 2003). The number of controls was determined by considering that an allocation ratio of 1:4 between PD patients and controls has a 92% power to detect a difference of 125 Ω in R_{sum500} at a level of alpha of 0.05 assuming an s.d. of 150 Ω for both PD patients and controls (Malavolti *et al*, 2003). Between-group comparisons of continuous variables were performed by Student's unpaired t-test and those of ordinal variables with Fisher's exact test. The adjusted coefficient of determination (R^2_{adj}), the root mean-squared error (RMSE) and the percent root mean-squared error (RMSE%) of the estimate obtained from linear regression of FFM or LTM *vs* RI_x were used to determine the accuracy of BIA (Guo & Chumlea, 1996). Measured and predicted values of FFM and LTM were also compared using Student's paired t-test. Statistical significance was set to a value of $P<0.05$ for all tests. Statistical analysis was performed on a MacOS computer using the Statview 5.1 and SuperANOVA 1.11 software packages (SAS, Cary, NC, USA).

Results

The measurements of PD patients and controls are given in Table 1. As a result of the matching procedure, gender ($P=0.999$), age ($P=0.947$) and BMI ($P=0.773$) were similar in PD patients and controls. Even if PD patients were lighter ($P=0.034$) and shorter ($P=0.0007$) than controls, their FFM ($P=0.524$), LTM_{arm} ($P=0.442$) and LTM_{leg} ($P=0.179$) were similar to those of controls. FM was lower in PD patients than controls, but the difference did not reach statistical significance ($P=0.081$). At all frequencies, R_{sum}, R_{arm} and R_{leg} were lower in PD patients than in controls (values of R at 500 kHz are given in Table 1).

The variance of FFM, LTM_{arm} and LTM_{leg} explained by R and RI is given in Table 2. As expected from electrical theory (Bedogni *et al*, 2002), the variance of FFM, LTM_{arm} and LTM_{leg} explained by R and RI increased for increasing frequencies. Even if R was a more accurate predictor of body composition in PD patients than in controls, the accuracy of RI was similar in PD patients and controls. On balance, the

Table 1 Measurements of PD patients and controls

	PD patients (n = *20*)	*Controls* (n = *77*)	P-*value*[a]
Gender (M/F)	9/11	36/41	0.999
Age (y)	53 ± 19	53 ± 17	0.947
Wt (kg)	64.4 ± 8.2	70.7 ± 11.4	0.034
Ht (m)	1.60 ± 0.07	1.68 ± 0.09	0.0007
BMI (kg/m^2)	25.3 ± 3.2	25.0 ± 3.2	0.773
FFM (kg)	49.0 ± 7.9	50.7 ± 10.6	0.524
FM (kg)	14.6 ± 6.4	17.6 ± 6.6	0.081
LTM_{arm} (kg)[b]	2.3 ± 0.6	2.5 ± 0.7	0.442
LTM_{leg} (kg)[b]	7.4 ± 0.9	8.0 ± 1.7	0.179
R_{sum500} (Ω)	875 ± 147	1006 ± 142	0.009
R_{arm500} (Ω)[b]	247 ± 44	276 ± 46	0.019
R_{leg500} (Ω)[b]	185 ± 32	219 ± 29	<0.0001

PD = peritoneal dialysis; Wt = weight; Ht = height; BMI = body mass index; FFM = fat-free mass; FM = fat mass; LTM = lean tissue mass; R_{sum500} = whole-body resistance at 500 kHz; R_{arm500} = arm resistance at 500 kHz; R_{leg500} = leg resistance at 500 kHz.
[a]Fisher's exact test for nominal variables and Student's unpaired t-test for continuous variables.
[b]Mean of left and right sides.

Table 2 Variance of whole-body FFM and appendicular LTM explained by whole-body or segmental bioelectrical resistance and the RI in PD patients and controls

	R^2_{adj}*					
	FFM		*LTM_{arm}*[a]		*LTM_{leg}*[a]	
	PD patients	*Controls*	*PD patients*	*Controls*	*PD patients*	*Controls*
R_5	0.72	0.53	0.71	0.57	0.55	0.39
R_{50}	0.77	0.58	0.76	0.59	0.63	0.48
R_{250}	0.76	0.61	0.76	0.61	0.66	0.52
R_{500}	0.75	0.62	0.75	0.62	0.66	0.52
RI_5	0.82	0.90	0.83	0.91	0.79	0.60
RI_{50}	0.90	0.91	0.89	0.92	0.84	0.68
RI_{250}	0.92	0.92	0.91	0.93	0.85	0.72
RI_{500}	0.92	0.92	0.91	0.93	0.85	0.75

R^2_{adj} = adjusted coefficient of determination; FFM = fat-free mass; LTM = lean tissue mass; PD = peritoneal dialysis; R_x = resistance at frequency x; RI = resistance index at frequency x.
*$P<0.0001$ for all values of R^2_{adj}.
[a]Mean of left and right sides.

Table 3 Algorithms for the prediction of whole-body FFM and appendicular LTM from the whole-body or segmental RI at 500 kHz in PD patients and controls

Y	*X*	b_0	b_1	R^2_{adj}*	*RMSE (kg) (%)*	*Bias (kg)***
FFM—controls	RI_{sum500}	2.225	1.683	0.92	3.0 (6%)	0.0 ± 3.0
LTM_{arm}—controls[a]	RI_{arm500}	−0.643	0.029	0.93	0.2 (8%)	0.0 ± 0.2
LTM_{leg}—controls[a]	RI_{leg500}	0.095	0.060	0.75	0.7 (8%)	0.0 ± 0.7
FFM—PD patients	RI_{sum500}	9.742	1.291	0.92	2.3 (5%)	0.0 ± 2.3
LTM_{arm}—PD patients[a]	RI_{arm500}	−0.362	0.025	0.91	0.2 (8%)	0.0 ± 0.2
LTM_{leg}—PD patients[a]	RI_{leg500}	3.023	0.030	0.85	0.5 (7%)	0.0 ± 0.5

Y = dependent variable; *X* = predictor variable; b_0 = intercept; b_1 = slope; R^2_{adj} = adjusted determination coefficient; RMSE = root mean-squared error; bias = difference between body composition predicted by bioelectrical impedance analysis and measured by dual-energy X-ray absorptiometry; FFM = fat-free mass; LTM = lean tissue mass; PD = peritoneal dialysis.
*$P<0.0001$ for all values of R^2_{adj}.
**Mean ± s.d.; $P \geq 0.999$ for BIA *vs* DXA for all values (Student's paired *t*-test).
[a]Mean of left and right sides.

best predictions of total and appendicular body composition were obtained from RI_{500} in both PD patients and controls. As compared to RI_{sum500}, Wt explained 51% less variance of FFM in PD patients ($R^2_{adj} = 0.41$, $P = 0.003$) and 32% less in controls ($R^2_{adj} = 0.60$, $P < 0.0001$).

The predictive algorithms obtained by regressing FFM, LTM_{arm} and LTM_{leg} *vs* RI_{500} in controls are given in Table 3. Wt explained only 8% ($P = 0.006$) of the variance of FFM unexplained by RI_{500} and its inclusion in the model as predictor did not improve the estimate, as shown by an unchanged RMSE%.

When the algorithms developed on controls were applied to PD patients, they overestimated FFM (4.1 ± 3.4 kg, mean ± s.d., $P<0.0001$, Student's paired *t*-test) and LTM_{arm} (0.15 ± 0.21 kg, $P<0.0001$) and underestimated LTM_{leg} (−0.85 ± 0.73 kg, $P<0.0001$). Specific regression equations were thus developed for PD patients (Table 3) and their comparison with those of controls revealed significantly different slopes ($P = 0.002$ for FFM, $P = 0.030$ for LTM_{arm} and $P<0.0001$ for LTM_{leg}) (Figure 2). Wt ($P = 0.880$) and PD duration ($P = 0.792$) did not explain any portion of residual FFM variance.

Discussion

In this study, we evaluated the accuracy of eight-polar BIA for the assessment of whole-body FFM and appendicular LTM in PD patients. BIA was crossvalidated against DXA, which allows an accurate assessment of body composition in dialysis patients (Locatelli *et al*, 2002). The use of DXA is nonetheless restricted to selected centers because of technical and logistical reasons. On the contrary, BIA is portable and can be employed in field studies of body composition.

The body composition of our PD patients was not significantly different from that of healthy subjects of the same age, sex and body mass index. The FFM:Wt ratio tended, however, to be higher in PD patients than in

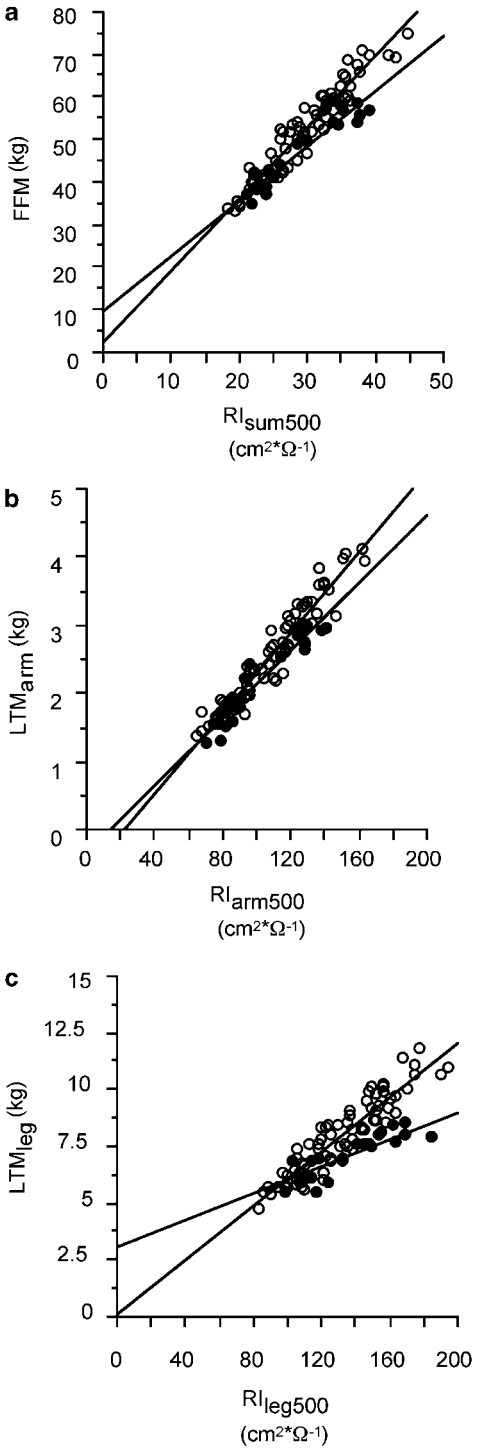

Figure 2 Regression lines for the prediction of whole-body FFM and appendicular LTM (mean of left and right sides) from the whole-body or segmental resistance index at 500 kHz in peritoneal dialysis patients (black points, $n=20$) and controls (white points, $n=77$). FFM = fat-free mass; LTM = lean tissue mass; RI_{sum500} = whole-body resistance index at 500 kHz; RI_{arm500} = arm resistance index at 500 kHz; RI_{leg500} = leg resistance index at 500 kHz.

controls (76±9 *vs* 72±9, $P=0.075$), partly because of the lower FM ($P=0.081$). The fact that our patients were undergoing PD from a median of only 4 months may partly explain why we were not able to detect gross differences in body composition between PD patients and controls. Patients undergoing PD from longer periods have been in fact found to have lower whole-body FFM, appendicular LTM and higher FM than healthy controls (Woodrow *et al*, 1996b). Interestingly, the values of whole-body and segmental *R* were lower in PD patients than in controls at all frequencies. As *R* is inversely related to TBW (Bedogni *et al*, 2002), this can be taken as indirect evidence of TBW expansion in PD patients, at least as compared to controls. This may have contributed to the higher FFM:Wt ratio of PD patients in addition to their lower FM.

As in our previous studies of eight-polar BIA (Bedogni *et al*, 2002; Malavolti *et al*, 2003; Sartorio *et al*, 2005), *R* and RI were highly associated with total and appendicular body composition and the strength of this association increased with increasing frequencies. The fact that *R* was a better predictor of body composition in PD patients than in controls was unexpected, but may be partly explained by a different interindividual variability in body composition between PD patients and controls. For instance, the coefficient of variation of FFM was lower in PD patients than in controls (16 *vs* 21%). RI was, however, an equally accurate predictor of body composition in PD patients and controls and was clearly the best indicator of body composition in the two groups.

We consider of great importance the fact that RI (and to some extent *R*) was superior to Wt as a predictor of FFM and that Wt did not add to the prediction of FFM obtained from RI. A critique correctly raised to BIA is in fact that it should contribute to the estimate of body composition substantially more than Wt or other anthropometric parameters (Bedogni *et al*, 2003). The present study extends to PD patients our previous demonstration of the superiority of eight-polar BIA to Wt in the prediction of body composition in healthy and obese individuals (Bedogni *et al*, 2002; Malavolti *et al*, 2003; Sartorio *et al*, 2005). It is also of some interest that Wt explained only 41% of the variance of FFM in PD patients as compared to a value of 60% in controls. This finding suggests that Wt is a less adequate indicator of body composition in PD patients than it is in healthy subjects and highlights the potential of BIA for the assessment of body composition in disease states.

The relationships between RI_{500} and total and appendicular body composition were different in PD patients and controls, as shown by different regression slopes and by the overestimation of FFM and LTM_{arm} and the underestimation of LTM_{leg} observed when the equations developed on controls were applied to PD patients. However, using population-specific algorithms, the accuracy of the estimate was similar in PD patients *vs* controls, as shown by values of RMSE% of 5 *vs* 6% for FFM, 8 *vs* 8% for LTM_{arm} and 7 *vs* 8% for LTM_{leg}. More importantly, also the individual bias was

similar in patients *vs* controls, with values of 0.0 ± 2.3 *vs* 0.0 ± 3.0 kg for FFM, 0.0 ± 0.2 *vs* 0.0 ± 0.2 kg for LTM_{arm} and 0.0 ± 0.5 *vs* 0.0 ± 0.7 kg for LTM_{leg}. As is true of every predictive algorithm (Guo & Chumlea, 1996), the equations developed in this study should undergo crossvalidation in external samples before being employed for research purposes. Such crossvalidation should consider that these algorithms were developed in patients undergoing PD from only few months and whose body composition did not differ substantially from that of healthy subjects of the same age and sex.

In conclusion, eight-polar BIA provides accurate estimates of total and appendicular body composition in PD patients. These estimates are as accurate as those obtained in healthy subjects. However, population-specific equations have to be employed for this purpose. Eight-polar BIA shows a great potential for the study of appendicular muscle mass in PD patients, but further studies are needed to evaluate its ability to assess body composition changes.

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