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ORIGINAL COMMUNICATION

New bioimpedance analysis system: improved phenotyping with whole-body analysis

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Objective: Bioimpedance analysis (BIA) is a potential field and clinical method for evaluating skeletal muscle mass (SM) and %fat. A new BIA system has 8-(two on each hand and foot) rather than 4-contact electrodes allowing for rapid 'whole-body' and regional body composition evaluation.
Design: This study evaluated the 50 kHz BC-418 8-contact electrode and TBF-310 4-contact electrode foot–foot BIA systems (Tanita Corp., Tokyo, Japan).
Subjects: There were 40 subject evaluations in males ($n=20$) and females ($n=20$) ranging in age from 6 to 64 y. BIA was evaluated in each subject and compared to reference lean soft-tissue (LST) and %fat estimates in the appendages and remainder (trunk + head) provided by dual-energy X-ray absorptiometry (DXA). Appendicular LST (ALST) estimates from both BIA and DXA were used to derive total body SM mass.
Results: The highest correlation between total body LST by DXA and impedance index (Ht^2/Z) by BC-418 was for the foot–hand segments ($r=0.986$; left side only) compared to the arm ($r=0.970$–0.979) and leg segments ($r=0.942$–0.957)(all $P<0.001$). The within- and between-day coefficient of variation for %fat and ALST evaluated in five subjects was $<1\%$ and ~ 1–3.7%, respectively. The correlations between 8-electrode predicted and DXA appendicular (arms, legs, total) and trunk + head LST were strong and highly significant (all $r \geqslant 0.95$, $P<0.001$) and group means did not differ across methods. Skeletal muscle mass calculated (Kim equation) from total ALST by DXA ($X \pm$ s.d.)(23.7 ± 9.7 kg) was not significantly different and highly correlated with BC-418 estimates (25.2 ± 9.6 kg; $r=0.96$, $P<0.001$). There was a good correlation between total body %fat by 8-electrode BIA *vs* DXA ($r=0.87$, $P<0.001$) that exceeded the corresponding association with 4-electrode BIA ($r=0.82$, $P<0.001$). Group mean segmental %fat estimates from BC-418 did not differ significantly from corresponding DXA estimates. No between-method bias was detected in the whole body, ALST, and skeletal muscle analyses.
Conclusions: The new 8-electrode BIA system offers an important new opportunity of evaluating SM in research and clinical settings. The additional electrodes of the new BIA system also improve the association with DXA %fat estimates over those provided by the conventional foot–foot BIA.
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Introduction

Bioimpedance analysis (BIA) systems are increasingly being used to quantify body composition in clinical and research setting (de Fijter *et al*, 1993; Organ *et al*, 1994; Bracco *et al*, 2000; Lukaski, 2000; Bedogni *et al*, 2002; Fuller *et al*, 2002; Nunez *et al*, 2003). An important advance over the past several years was the introduction of contact electrode systems that eliminated the need for stainless-steel paste-on gel electrodes (Nunez *et al*, 1997; Tan *et al*, 1997). Most of the currently available contact electrode BIA systems estimate electrical properties across the arms (Cornish *et al*, 1999; Elia *et al*, 2000) and across the legs (Elia *et al*, 2000). Leg-to-leg BIA systems have the advantage of providing a body weight measurement using a standard digital scale concurrent with foot-pad impedance or resistance estimates. Measured body weight is more accurate than self-reported weight and the measured weight is used directly in the body composition calculations.

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Another important advance in the BIA body composition field was the introduction by Organ *et al* (1994), of simple means by which to make segmental measurements. The scheme developed by Organ *et al* (1994) allowed electrical measurements of specific segments without the need for proximal electrode placement. The resistance, reactance, and impedance of each arm and leg and the trunk thus can be easily quantified using hand and foot contact electrodes (Cornish *et al*, 1999; Elia *et al*, 2000).

The opportunity to estimate segmental electrical properties offers the opportunity to estimate appendicular lean soft tissue (ALST), mainly skeletal muscle (Pietrobelli *et al*, 1998a). A strong correlation is present between appendicular resistance or impedance and ALST (Pietrobelli *et al*, 1998a). Adjusting measured resistance/impedance for either limb length or height then allows development of BIA ALST prediction equations. ALST mass can also be used in the Kim equation to predict total body skeletal muscle mass (SM) (Kim *et al*, 2002).

Taken collectively, these observations suggest the possibility of developing a multi-contact electrode BIA system for field and clinical use that can rapidly provide regional body composition measurements, including SM, in addition to whole-body estimates. In this report, we evaluate a new 8-contact electrode BIA system designed for field and clinical applications that provides whole-body and regional body composition estimates.

Methods

Experimental design

Each subject completed segmental BIA, foot–foot BIA, and DXA at the Body Composition Unit (Obesity Research Center, St Luke's/Roosevelt Hospital, New York, USA). All subjects, including the children's parents, signed an informed consent form prior to participation. The study was approved by the Institutional Review Board of St Luke's/Roosevelt Hospital.

Subjects

The subjects (20 male and 20 female subjects) ranged in relative weight from normal to obese and were over the age of 5 y. Recruitment was from among Hospital employees, volunteers, and local community residents. Health status was assessed by self-report and individuals with serious chronic diseases (eg, active malignancy) that influenced body composition were excluded from participating in this research. None of the subjects reported a history of endocrine, nutritional, or growth disorders nor were any presently dieting or experienced weight loss ≥ 3 kg over the previous 6 months.

Body composition

Anthropometry. The subject's body weight was measured to the nearest 0.1 kg. using a Weight–Tronix electronic scale (Scale Electronics Development, New York, USA). Height was measured without shoes to the nearest 0.5 cm using a stadiometer (Holtain, Crosswell, Wales, UK). Body mass index (BMI) was calculated as weight (kg) divided by height (m) squared (kg/m^2).

Bioimpedance analysis. The BC-418 8-contact electrode system (Tanita Corp., Tokyo, Japan) was designed to collect multiple sets of whole-body and segmental impedance measurements without the need for placement of conventional gel electrodes. The system base has two stainless-steel rectangular foot-pad electrodes fastened to a metal platform set on force transducers for weight measurement. Each of the extremity hand-grip electrodes has an anterior and posterior portion. Hence, there are four separate foot-pad electrodes mounted on the system's base and two electrodes in each of the hand grips. The eight electrodes are connected to a digital circuit board that electronically switches the electrical circuit under study. A predefined signal is passed through injector electrodes and impedance across the subject's tissues is measured with receiver electrodes. All measurements are carried out at 50 kHz with a 0.8 mA sine wave constant current.

The electrode configuration protocol is based on the study of Organ *et al* (1994). A total of five segments are measured, each arm, each leg, and remainder (trunk + head); whole body is measured as the foot–hand electrical pathway. The system provides impedance estimates for the foot–hand (right side), arm, and leg electrical pathways. LST and %fat estimates are provided for each of the regions and %fat for the 'whole-body' is based on the left foot–hand impedance measurement. The 'trunk + head' estimates are based on the difference between total body estimate and the corresponding appendicular estimates. We also calculated ALST as the sum of arm and leg LST estimates and then used Kim's equation (Kim *et al*, 2002) to calculate total body SM $(\mathrm{kg}) = 1.19 \times \mathrm{ALST}\ (\mathrm{kg}) - 1.01$.

We examined operational characteristics of the new system by evaluating the within- and between-day coefficient of variations (CV; 100 × [s.d./mean]) for impedance in five subjects (two men and three women). The within-day CV was determined by measuring each subject a total of 10 times within a 1 h time period. The between-day CV was determined by evaluating each subject on five consecutive days.

The foot-to-foot system (BC-310, Tanita Corp., Tokyo, Japan) incorporates the electrodes into a precision electronic scale. The scale consists of a load cell that transforms platform weight into an electrical signal. The stainless-steel BIA electrodes are mounted on the system's platform and are shaped as two large feet. Each foot-pad is divided in half so that the anterior and posterior portions form two separate electrodes. Current is applied to the anterior foot pad electrodes and the voltage drop across the posterior heel electrodes is then measured. Impedance (50 kHz–0.8 mA) of the lower extremities and body weight are measured simultaneously while the subject is standing on the scale.

The computer software in both BIA systems uses the measured impedance, the programmed subject's sex and height, and the measured weight to calculate the body composition estimates based on previously derived equations obtained from regression analyses with dual energy X-ray absorptiometry (DXA) as the reference method. In an earlier study Nunez *et al* (1997) reported a within- and between-day coefficient of variation for %body fat of 0.9±0.5 and 2.1±1.0%, respectively.

The BIA measurements were carried out after the subject had rested for 15 min in a well-aired room with constant temperature and controlled relative humidity.

Dual energy X-ray absorptiometry. DXA was used to measure fat, LST, and bone mineral mass; %fat; and ALST. We then used Kim's (2002) equation to calculate total-body SM for DXA. The scan was completed with a whole-body pencil beam DPX system (Lunar Radiation Corp., Madison, WI, USA). Detailed methods for scan procedure and analysis are described in detail elsewhere (Pietrobelli *et al*, 1996, 1998a). Briefly, using specific anatomic landmarks, legs, arms, and trunk were isolated on the skeletal X-ray anterior view planogram using the DXA system's automated software. The DXA software then provided compositional estimates of legs, arms, trunk, head, and whole-body.

Statistical methods

All analyses were carried out using the statistical program SAS (SAS Institute Inc., Cary, USA). The group results are presented as mean±s.d. SM estimates are expressed in kg and fat estimates as a percent of body weight as is usual practice. Statistical significance was set at the 0.05 probability level, unless otherwise stated.

Paired *t*-tests were used to compare between measurement (DXA *vs* BIA) differences in body composition. Simple regression analysis was used to examine the relationship between BIA and DXA measurements (ie, ALST, total SM, %fat using BC-310 and BC-418 and DXA %fat). For the main associations, ALST, SM, and whole-body %fat we also checked for between-method bias using Bland–Altman analyses (Altman & Bland, 1983).

Results

Subject characteristics

Subject characteristics are summarized in Table 1. The 20 male and 20 female subjects ranged in age from 6 to 64 y with a mean of 28.6±18.3 y. Weight varied from 21.6 to 123.2 kg and BMI from 15.3 to 37.5 kg/m^2 with a mean of 24.8±6.1 kg/m^2.

Table 1 Baseline characteristics of study population

	Males	*Females*	*Total*
Number	20	20	40
Age (y)	27.7±19.1 (6–64)	29.5±16.9 (8–57)	28.6±18.3 (6–64)
Weight (kg)	73.6±29.9 (21.6–123.2)	62.3±17.1 (32.4–99.2)	67.9±25.3 (21.6–123.2)
Height (cm)	166.1±19.3 (119–190.2)	159.1±9.6 (137–176.8)	162.6±15.8 (119–190.2)
BMI (kg/m^2)	25.3±6.8 (15.3–37.5)	24.2±5.1 (17.3–36.7)	24.8±6.1 (15.3–37.5)

Results are expressed as mean±s.d. (range).

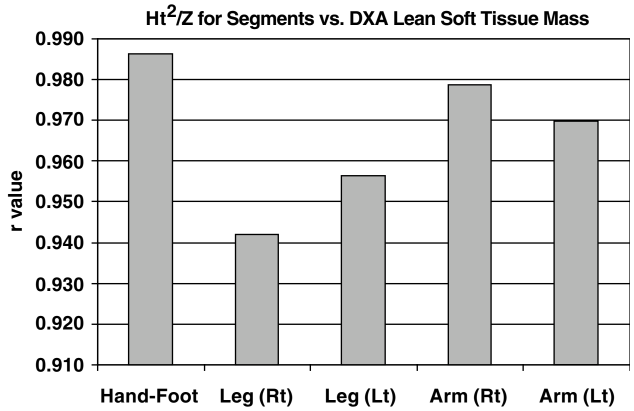

Figure 1 Correlations (*r*-values) for stature-adjusted impedance (H^2/Z) *vs* total-body LST mass by DXA.

Impedance measurements

The within-day CVs for %fat and ALST evaluated in five subjects were 0.8–1.4 and 0.3–0.6%, respectively. The corresponding between-day CVs were 2.3–3.7 and 1.1–2.2%, respectively.

Segment impedance estimates were available from the BC-418 for foot–hand, and both arms and legs. Segmental BIA estimates are usually adjusted for height^2 (ie, H^2/Z) as a measure of conductor volume. Accordingly, in the context of 'whole-body' prediction we examined the associations between H^2/Z for each of the provided segments and DXA and LST estimates. The results, shown in Figure 1, indicate the strongest association (*r*-value) for the hand-foot pathway ($r=0.986$), followed by each arm (right, $r=0.979$; left, $r=0.970$), and then by the two leg pathways (right, $r=0.942$; left, $r=0.957$). All *P*-values were <0.001.

Body composition

The results of LST body composition studies are presented in Table 2. There were no significant differences between mean DXA and BC-418 LST estimates for any of the measured segments (ie, each arm and leg and trunk + head), total ALST, or calculated SM and correlations were all very high

Table 2 Results of DXA and BIA total body and regional LST (kg) estimations

Measured segment	(*DXA*)	(*BC-418*)	P (*DXA* Vs *BC-418*)	(R*)
Left arm	2.6±1.4	2.4±1.2	0.60	0.96
Right arm	2.6±1.3	2.4±1.2	0.61	0.96
Left leg	7.4±2.9	7.7±2.9	0.75	0.96
Right leg	7.4±2.8	7.8±2.8	0.65	0.95
ALST	20.0±8.2	20.3±8.1	0.9	0.96
Trunk + head	24.5±9.3	26.7±8.5	0.60	0.98
Total body SM	23.8±9.7	25.2±9.6	0.90	0.96

ALST, appendicular lean soft tissue; SM, skeletal muscle mass. Results are expressed as the mean±s.d. *All *P*-values are <0.001.

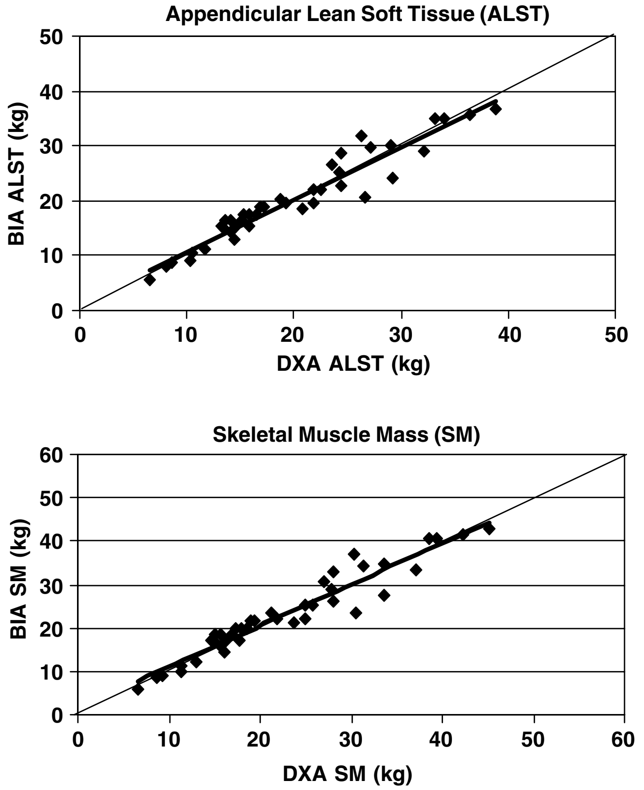

Figure 2 Upper: plot of ALST estimates by BIA (BC-418) *vs* DXA ($ALST_{BIA} = 0.95 \times ALST_{DXA} + 1.32$, $r = 0.96$, $P < 0.001$). Lower: Plot of SM estimates by BIA *vs* DXA (BC-418) ($SM_{BIA} = 0.95 \times SM_{DXA} + 1.5$, $r = 0.96$, $P < 0.001$). The regression and lines of identity are shown in the figures.

($r = \geq 0.95$, all $P < 0.001$). The plots for BC-418 *vs* DXA ALST ($ALST_{BIA} = 0.95 \times ALST_{DXA} + 1.32$, $r = 0.96$) and SM ($SM_{BIA} = 0.95 \times SM_{DXA} + 1.5$, $r = 0.96$, $P < 0.001$) are presented in Figure 2. There were no significant differences between BC-418 and DXA ALST (20.0±8.2 *vs* 20.3±8.1) and SM (23.8±9.7 *vs* 25.2±9.6). Bland–Altman (Altman & Bland, 1983) analyses failed to detect any between-method bias in ALST or SM analyses.

Table 3 Results of DXA and BIA total body and regional %fat estimations

Measured segment	(*DXA*)	(*BC-418*)	P (*DXA* vs *BC-418*)	(R*)
Left arm	26.6±12.1	30.4±10.3	0.29	0.80
Right arm	26.3±11.9	29.2±10.0	0.41	0.79
Left leg	30.8±10.8	30.9±10.0	0.97	0.85
Right leg	30.6±10.9	30.5±10.2	0.97	0.80
Trunk + head	28.9±10.8	25.2±9.7	0.13	0.81
Total	29.2±10.7	27.7±9.2	0.63	0.89
BC-310		27.0±10.6	0.90	0.83

Results are expressed as the mean±s.d. *All *P*-values are <0.001.

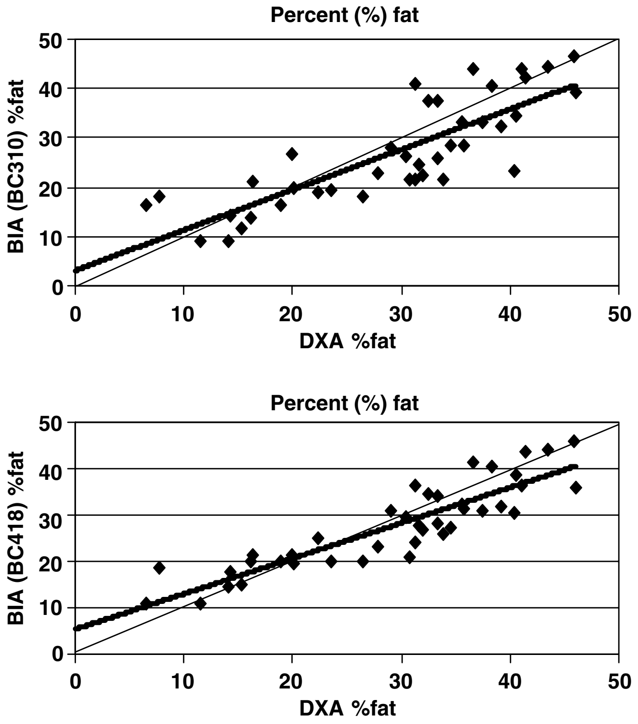

Figure 3 Upper: plot of %fat estimates by BIA (BC-310) *vs* DXA ($\%fat_{BIA} = 0.82 \times \%fat_{DXA} + 3.1$, $r = 0.82$, $P < 0.001$). Lower: plot of %fat estimates by BIA *vs* DXA (BC-418) ($\%fat_{BIA} = 0.76 \times \%fat_{DXA} + 5.4$, $r = 0.87$, $P < 0.001$). The regression and lines of identity are shown in the figures.

The results of %fat body composition studies are presented in Table 3. There were good correlations between BC-418 and DXA regional %fat estimates, ranging from $r = 0.79$ to 0.85, with all $P < 0.001$. None of the mean regional differences between BC-418 and DXA were significant. The %fat estimates for total body also did not differ significantly between DXA (29.2±10.7%) and either the BC-418 (27.7±9.2%) or BC-310 (27.0±10.6%) and the association between BIA and DXA was lower for the BC-310 ($\%fat_{BIA} = 0.82 \times \%fat_{DXA} + 3.1$, $r = 0.82$, $P < 0.001$) than for the BC-418 ($\%fat_{BIA} = 0.76 \times \%fat_{DXA} + 5.4$, $r = 0.87$, $P < 0.001$) (Figure 3).

Bland–Altman (1983) method failed to detect any between-method bias in the BC-310 %fat analysis. The BC-310 showed a small but significant bias ($P = 0.05$), but there was one outlier and the bias was no longer present when the analysis was repeated with the subject removed.

Discussion

The present study results support the accuracy of the segmental BIA system across a wide range of subject characteristics, including age and BMI. Specifically, the 8-contact electrode system provided high correlations comparable with group mean regional LST and whole-body SM estimates to the reference method, DXA. Additionally, the BC-418 showed improved whole-body %fat correlations with DXA compared to the BC-310 foot–foot system. This observation is supported by the highest correlation observed between total LST and H^2/Z for the foot–hand pathway compared to the arm or leg pathways.

Our study extends the work of Tan *et al* (1997) who reported the characteristics of a BIA electrode stand designed for rapid whole-body and segmental resistance and reactance measurements. The investigators observed high correlations between contact and gel electrodes and between segmental resistances measured by Organ's protocol (Organ *et al*, 1994) and conventionally measured segmental resistances. Cha *et al* (1997) reported a commercial BIA system of similar design capable of rapid upright electrical measurements and body weight. In a recent study Salinari *et al* (2003) examined lower limb SM mass and SM distribution estimated from BIA modeling fitted with measured resistance values along the leg. The relative error in BIA model SM estimates was in the range of 6–7.0% compared to corresponding DXA estimates. Kyle *et al* (2003) examined ALST as a useful measure of body muscle protein mass. A BIA equation to predict ALST was developed that included height^2/resistance, weight, gender, age, and reactance with DXA as the reference. The prediction model had an SEE of 1.1 kg in healthy volunteers and 1.5 kg in patients. These earlier studies provide additional support and rationale for the current multicontact electrode BIA system for regional and whole-body fat and SM research and clinical applications.

The present BIA system is single frequency, 50 kHz, and the addition of a multiple frequency chip would afford the opportunity to quantify fluid distribution (Plum *et al*, 2001). Additionally, improved prediction of some components at frequencies other than 50 kHz may be possible. Pietrobelli *et al* (1998a, 2002) in two separate studies observed increasing correlations between regional ALST and H^2/Z up to the 300 kHz tested.

Another possibility is that combinations of segmental measurements may improve prediction of whole-body components in some conditions. Pirlich *et al* (2003) investigated the value of segmental BIA for body cell mass (BCM) estimation in malnourished subjects and acromegaly. In all, 19 controls and 63 patients with either reduced (liver cirrhosis without and with ascites, Cushing's disease) or increased BCM (acromegaly) were evaluated. Whole-body and segmental BIA at 50 kHz was compared with BCM measured by total-body potassium. Multiple regression analysis was used to develop specific equations for BCM in each subgroup. Compared to whole-body BIA equations, the inclusion of arm resistance improved the specific equation in cirrhotic patients without ascites and in Cushing's disease. In acromegaly, inclusion of resistance and reactance of the trunk best described BCM. However, in controls and in cirrhotic patients with ascites, segmental impedance parameters did not improve BCM prediction. In contrast, Wotton *et al* (2000) were unable to find any advantage of multiple frequency segmental BIA in predicting total body water (TBW) in healthy adults. TBW was measured using deuterium dilution and Cole–Cole analysis was used to determine the impedance at the characteristic frequency (Z_c). The correlation between TBW and segmental BIA measures was not significantly higher than the correlation between TBW and whole-body BIA measures.

In summary, the present study demonstrates the capability of evaluating regional LST and whole-body SM with an 8-contact electrode BIA system. Alternatives for measuring regional and whole-body lean tissue components, such as DXA and magnetic resonance imaging, are costly and cannot be easily applied in field settings. Moreover, the addition of either foot electrodes or hand electrodes to foot–foot and hand–hand BIA systems, as is embodied by the BC-418, improves %fat estimates based on impedance index correlations and, as in the present study, comparison to the BC-310 foot–foot system. Segmental BIA systems thus provide important new research and clinical opportunities.

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