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ORIGINAL COMMUNICATION

Accuracy of an eight-point tactile-electrode impedance method in the assessment of total body water

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Objective: To establish the accuracy of an eight-polar tactile-electrode impedance method in the assessment of total body water (TBW).
Design: Transversal study.
Setting: University department.
Subjects: Fifty healthy subjects (25 men and 25 women) with a mean (s.d.) age of 40 (12) y.
Methods: TBW measured by deuterium oxide dilution; resistance (*R*) of arms, trunk and legs measured at frequencies of 5, 50, 250 and 500 kHz with an eight-polar tactile-electrode impedance-meter (InBody 3.0, Biospace, Seoul, Korea).
Results: An algorithm for the prediction of TBW from the whole-body resistance index at 500 kHz (height $^2/R_{500}$ where *R* is the sum of the segmental resistances of arms, trunk and legs) was developed in a randomly chosen subsample of 35 subjects. This algorithm had an adjusted coefficient of determination (r^2_{adj}) of 0.81 ($P < 0.0001$) and a root mean square error (RMSE) of 3.6 l (9%). Cross-validation of the predictive algorithm in the remaining 15 subjects gave an r^2_{adj} of 0.87 ($P < 0.0001$) and an RMSE of 3.0 l (8%). The precision of eight-polar BIA, determined by measuring *R* three times a day for five consecutive days in a fasting subject, was $\leq 2.8\%$ for all segments and frequencies.
Conclusion: Eight-polar BIA is a precise method that offers accurate estimates of TBW in healthy subjects. This promising method should undergo further studies of precision and its accuracy in assessing extracellular water and appendicular body composition should be determined.

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Introduction

The prediction of total body water (TBW) from bioelectrical impedance analysis (BIA) is commonly performed from whole-body resistance (*R*), ie the value of *R* obtained by applying an alternating current (a.c.) to an hemisome through electrodes located on the hands and feet (Deurenberg, 1994). The *R*-based predictor commonly employed by BIA algorithms is the 'resistance index' (RI), ie the ratio of squared height (Ht) to *R* (Bedogni *et al*, 1996, 1997). RI was originally devised because *R* is directly related to the length (*L*) and inversely related to the cross-sectional area (*S*) of an ohmic conductor. By multiplying *L* and *S* for *L*, it appears that *R* is directly proportional to the squared length ($L^2 = L*L$) and inversely proportional to the volume ($V = S*L$) of a cylinder, so that *V* can be calculated from L^2/R. RI was indeed devised by assuming that the human body behaves like an ideal ohmic conductor of length Ht.

However, the human body is not an ohmic conductor, mainly because it is anisotropic, ie it cannot be transversed by a constant current density (Baumgartner *et al*, 1989). Moreover, as far as volume is concerned, the body is better approximated by five cylinders (two for the arms, one for the

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trunk and two for the legs) than by a single cylinder (Kushner, 1992). Because *R* is inversely related to *S*, arms and legs contribute more than trunk to whole-body *R* (Baumgartner *et al*, 1989). This has led to the suggestion that segmental RI (obtained by dividing the squared *L* of a segment by its resistance) may be more appropriate than whole-body RI to predict body composition (Baumgartner *et al*, 1989).

Only two studies have been performed so far as the prediction of TBW from segmental RI is concerned and in both of them *R* was measured at a single frequency of 50 kHz (Organ *et al*, 1994; Wotton *et al*, 2000). From the data of Organ *et al* (1994), a standard error of the estimate (s.e.e.) of 7% can be calculated for the prediction of TBW from whole-body RI in men and women. The corresponding value for the prediction of TBW from segmental RI (arms, trunk and legs) is 7% for men and 6% for women. From the data of Wotton *et al* (2000), an s.e.e. of 10% can be calculated for the prediction of TBW from whole-body RI and one of 9% for the prediction from segmental RI (arms, trunk and legs) in both men and women.

Recently, an eight-point tactile-electrode impedance-meter was developed and made available (InBody 3.0, Biospace, Seoul, Korea). We found this method attractive for two reasons: (1) the use of tactile electrodes for measuring segmental resistances at multiple frequencies; and (2) the absence of need to standardize the subject's posture before BIA. These characteristics have the potential to reduce measurement times and make this instrument ideal for epidemiological studies. This is especially true when subject's posture is considered, because 10–15 min are needed to standardize fluid distribution with four-polar BIA (Deurenberg, 1994).

This study aimed therefore at evaluating the accuracy of eight-polar BIA for the assessment of TBW.

Materials and methods

Subjects

Fifty healthy subjects (25 males and 25 females) with a mean (s.d.) age of 40 (12) y were enrolled in the study. They were recruited mainly among the personnel working at the Department of Biomedical Sciences of Modena and Reggio Emilia University. Inclusion criteria were: (1) age ≥ 18 y; (2) body mass index (BMI) $>18.5\,\mathrm{kg/m^2}$ (ie not underweight) and BMI $<30.0\,\mathrm{kg/m^2}$ (ie not obese); (3) absence of chronic (eg diabetes) and acute (eg influenza) disease, as determined by clinical history and physical examination; and (4) menstrual cycle between the 1st and 15th day for women. 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 100 g and total body height (Ht) to the nearest 0.1 cm using an electronic balance with an incorporated stadiometer (Tanita, Tokyo, Japan). BMI was calculated as Wt (kg)/Ht (m)^2. Acromial height and sitting height were measured using a portable anthropometer (Holtain, Crymich, UK). Leg length was obtained by subtracting sitting height from total body Ht, the height of head and neck by subtracting acromial height from total body Ht, and trunk height by subtracting the height of head and neck from sitting height. Arm length was measured as the distance between the lateral tip of the acromion and a line joining the bony prominences of radius and ulna on the dorsum of wrist (Organ *et al*, 1994). The distance between the line joining the bony prominences of radius and ulna and the 3rd metacarpal joint was also measured and summed to arm length in order to better approximate the true conductor length assumed by the eight-polar bioelectrical model of the arm. (With eight-polar BIA electrodes are located at the level of thumb and palm while with four-polar BIA they are positioned at the wrist level; see below). Triceps skinfold (TSF) and arm circumference (AC) were measured on the left side to the nearest 0.1 cm using a skinfold caliper and an anthropometric tape, respectively (Holtain, Crymich, UK). Arm muscle area (AMA) and arm fat area (AFA) were calculated from AC and TSF as described by Heymsfield *et al* (1982).

Eight-polar BIA

R of arms, trunk and legs was measured in fasting subjects at frequencies of 5, 50, 250 and 500 kHz using 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).

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 operation is performed with *V* recorded between E4 and E8 to obtain the 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 precaution was taken to standardize the subject's posture before BIA, as suggested by the manufacturer. Values of RI were calculated at all frequencies as follows:

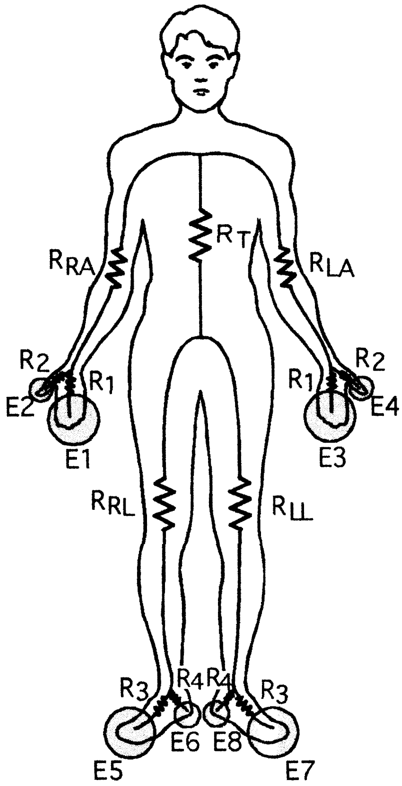

Figure 1 Measurement pathways of InBody 3.0 (graph reproduced by courtesy of Biospace). The subject stands with her or his soles in contact with the foot electrodes and grabs the hand electrodes. R_{RA}, resistance of right arm; R_T, resistance of trunk; R_{LA}, resistance of left arm; R_{RL}, resistance of right leg; R_{LL}, resistance of left leg. See text for details.

(1) arm (A)

$$\mathrm{RI_A} = \frac{\text{arm length (cm)}^2}{R_A(\Omega)}$$

(2) leg (L)

$$\mathrm{RI_L} = \frac{\text{leg length (cm)}^2}{R_L(\Omega)}$$

(3) trunk (T)

$$\mathrm{RI_T} = \frac{\text{trunk height (cm)}^2}{R_T(\Omega)}$$

(4) whole body (SUM)

$$\mathrm{RI_{SUM}} = \frac{\text{total body Ht (cm)}^2}{R_{RA}(\Omega) + R_{LA}(\Omega) + R_T(\Omega) + R_{RL}(\Omega) + R_{LL}(\Omega)}$$

Deuterium oxide dilution

TBW was measured by deuterium oxide (^2H_2O) dilution. Each fasting subject received a precisely weighed solution made up of ^2H_2O and drinkable water. Urine samples were collected before the administration of this solution and 4 h later. Subjects refrained from eating and drinking during the equilibration period of the tracer. ^2H_2O concentration in urine was measured by FT-IR spectrophotometry using the method of Lukaski and Johnson (1985). TBW was calculated as (^2H_2O dilution space*0.95), taking into account non-aqueous distribution of ^2H_2O (Schoeller, 1996).

Statistical analysis

Statistical analysis was performed on a MacOS computer using the Statview 5.1 (SAS, Cary, NC, USA) and SPSS 10 (SPSS, Chicago, IL, USA) software packages. Between-group comparisons were performed by unpaired *t*-tests and within-group comparisons by paired *t*-tests. Statistical significance for these tests was set to a value of $P < 0.05$. Bonferroni's correction was applied to between-group and between-hemisome comparisons of *R* values because of the number of tests involved. The significant *P*-value for these comparisons was put equal to 0.01 (0.05/3) because they were made in three groups (all subjects, males and females). The adjusted determination coefficient (r^2_{adj}), the root mean square error (RMSE) and the percentage root mean square error (RMSE% = RMSE/mean value of the dependent variable) obtained from linear regression of TBW *vs* RI were used to determine the accuracy of BIA (Guo *et al*, 1996; Glantz & Slinker, 2001). An interaction term between RI and sex (RI* sex) was added to test the influence of sex on the relationship between TBW and RI. Measured and predicted values of TBW were also compared using paired *t*-tests.

The precision of InBody 3.0 was determined by measuring *R* three times a day for five consecutive days on one of the study subjects. The between-day CV [(s.d./mean)*100] calculated from these measurements ($n = 15$) are given in Table 1. According to these values, the precision of InBody 3.0 is quite good and comparable to that of four-polar total-body BIA performed at 50 kHz (CV = 3.0% for between-day measurements; Deurenberg, 1994; Heitmann, 1994).

Results

The anthropometric measurements and TBW of the subjects are given in Table 2.

Age was not significantly different in males and females ($P = 0.47$). As expected, men were heavier ($P < 0.0001$) and

Table 1 Precision of eight-polar BIA. Values are coefficients of variation calculated from three measurements performed 1 h from each other for five consecutive days

	Trunk	*Right arm*	*Left arm*	*Right leg*	*Left leg*
R_5	2.8	2.0	2.8	2.5	2.5
R_{50}	2.2	1.8	2.6	2.3	2.3
R_{250}	1.7	1.9	2.3	2.4	2.2
R_{500}	2.2	1.8	2.3	2.3	2.0

R_x, resistance at x kHz.

Table 2 Measurements of the study subjects. Values are means and standard deviations

	All	*Female*	*Male*
n	50	25	25
Age (y)	40 ± 12	39 ± 12	41 ± 12
Wt (kg)	72.7 ± 14.5	62.2 ± 9.8	81.2 ± 12.1***
Ht (m)	1.71 ± 0.09	1.64 ± 0.06	1.77 ± 0.07***
BMI (kg/m^2)	24.4 ± 3.5	23.0 ± 3.4	25.8 ± 3.1*
AMA (cm^2)	41.7 ± 17.5	27.4 ± 5.8	56.0 ± 12.8***
AFA (cm^2)	28.4 ± 8.5	31.9 ± 8.2	24.8 ± 7.4**
TBW (l)	39.9 ± 8.1	33.9 ± 4.2	46.0 ± 6.5***
TBW:Wt (%)	55.9 ± 4.3	54.9 ± 4.5	56.8 ± 3.9

*$P = 0.002$, **$P = 0.004$; and ***$P < 0.0001$ *vs* female.

Wt, weight; Ht, height; BMI, body mass index; AMA, arm muscle area; AFA, arm fat area; TBW, total body water.

taller ($P < 0.0001$) than women, and had higher values of BMI ($P = 0.002$), AMA ($P < 0.0001$) and AFA ($P = 0.004$).

TBW was higher in males than females ($P < 0.0001$) but body hydration, calculated as TBW:Wt, was similar ($P = 0.12$). This unexpected finding implies that the study women had more fat-free tissues per unit of Wt than the 'average woman' does. This is supported by the fact that our women had a BMI lower than average (23.0 kg/m^2) and an inter-individual variability in AMA and AFA comparable to that of men (CV = 21 *vs* 23% for AMA and CV = 26 *vs* 30% for AFA). The values of *R* are given in Table 3.

Table 3 Resistance measurements of the study subjects. Values are means and standard deviations

	Resistance (Ω)			
	5 kHz	*50 kHz*	*250 kHz*	*500 kHz*
Trunk	27 ± 4	21 ± 3	18 ± 3	16 ± 3
Right arm	365 ± 63†	318 ± 58	284 ± 54‡	274 ± 52‡
Left arm	370 ± 66	325 ± 60	292 ± 56	281 ± 55
Right leg	288 ± 39	253 ± 37	226 ± 34	219 ± 22
Left leg	290 ± 41	254 ± 39	227 ± 36	220 ± 34
Sum	1340 ± 202	1171 ± 185	1046 ± 175	1011 ± 169

$^\dagger P = 0.004$ and $^\ddagger P < 0.0001$ *vs* left side
(statistical significance set to a value of $P < 0.01$ owing to multiple comparisons).

In the pooled sample, R_{RA} was lower than R_{LA} at frequencies of 5 ($P = 0.004$), 250 ($P < 0.0001$) and 500 ($P < 0.0001$) kHz but R_{RL} and R_{LL} were not significantly different (Table 3). *R* was consistently lower in males than females for all segments frequencies ($P \leq 0.005$; data not shown), owing to their higher TBW. The relationships between *R*, RI and TBW are given in Table 4.

R explained a quote of TBW variance comprised between 33 (R_{T5}) and 65% (R_{RA250}, R_{RA500} and R_{SUM500}). A trend to an increase in the explained variance of TBW was seen at increasing frequencies, as expected from electrical theory (Table 4). The sex**R* interaction was significant ($P < 0.05$) for limbs and whole body at frequencies ≥ 250 kHz (data not shown). Although this suggests the need to consider separately males and females, we chose not to do this for descriptive reasons, for RI allowed a better prediction of TBW as compared to *R* alone (Table 4) and none of the sex*RI interactions was significant (data not shown).

The best prediction of TBW from RI was obtained from $\mathrm{RI}_{\mathrm{SUM500}}$ at 500 kHz ($r^2_{\mathrm{adj}} = 0.83$, RMSE = 3.4 l, RMSE% = 9%, $n = 50$; cf. Table 4). When total body Ht was used instead of segmental length as the numerator of RI, the results were unchanged or slightly better (data not shown). This shows that with eight-polar BIA there is no practical advantage in using segmental lengths instead of total body height as the numerator of RI.

It has been suggested that segmental RI may be employed to predict TBW by means of multiple regression models (Organ *et al*, 1994; Wotton *et al*; 2000). Besides not being superior to simple regression from $\mathrm{RI}_{\mathrm{SUM500}}$, this approach was prone to multicollinearity in our subjects (variance inflation factors ≥ 6.5) and thus we preferred to avoid it. The presence of multicollinearity was not unexpected because all RI have length^2 as their numerator and the values of *R* at their denominator are highly correlated (Glantz & Slinker, 2001).

Thus, $\mathrm{RI}_{\mathrm{SUM500}}$ was the best predictor on both theoretical and practical grounds. In order to develop a predictive algorithm of TBW based on $\mathrm{RI}_{\mathrm{SUM500}}$ and test its accuracy, we randomly split the study sample in two sub-samples. Following the recommendations of Guo *et al* (1996), two-thirds of the sample ($n = 35$) were used to generate a predictive equation of TBW from $\mathrm{RI}_{\mathrm{SUM500}}$ and the remaining

Table 4 Variance of total body water explained by BIA ($n = 50$). Values are adjusted coefficients of determination

	R_5	RI_5	R_{50}	RI_{50}	R_{250}	RI_{250}	R_{500}	RI_{500}
Trunk	0.33	0.56	0.47	0.66	0.44	0.64	0.41	0.63
Right arm	0.64	0.80	0.57	0.75	0.65	0.81	0.65	0.81
Left arm	0.61	0.78	0.53	0.74	0.62	0.79	0.62	0.79
Right leg	0.48	0.73	0.55	0.76	0.57	0.78	0.56	0.78
Left leg	0.43	0.71	0.51	0.75	0.49	0.74	0.52	0.76
Sum	0.61	0.81	0.61	0.80	0.64	0.82	0.65	0.83

$P < 0.0001$ for all values.
R_x, resistance at *x* kHz; RI_x, resistance index (segmental length^2/*R* for trunk and limbs, and height^2/*R* for sum) at *x* kHz.

one-third ($n=15$) was used to test its accuracy. The results of this procedure are shown in Figure 2.

The predictive algorithm based on RI_{SUM500} explained 81% of TBW variance ($P<0.0001$) and had an RMSE of 3.61 (9%). There was no significant difference between TBW estimated from BIA and TBW measured by ^2H_2O (40.6 ± 7.3 *vs* 40.6 ± 8.1 l; $P=0.99$). The validation of the algorithm proved to be equally good, with an r^2_{adj} of 0.87, a RMSE of 3.01 (8%), a pure error of 3.11 and a mean (s.d.) estimated value of 38.5 (7.5) l *vs* a measured one of 38.3 (8.2) l ($P=0.99$).

Discussion

In this study, we evaluated the accuracy of a newly developed eight-polar tactile-electrode impedance-meter. Making use of tactile electrodes and requiring no standardization of the subject's posture before measurements, this method may

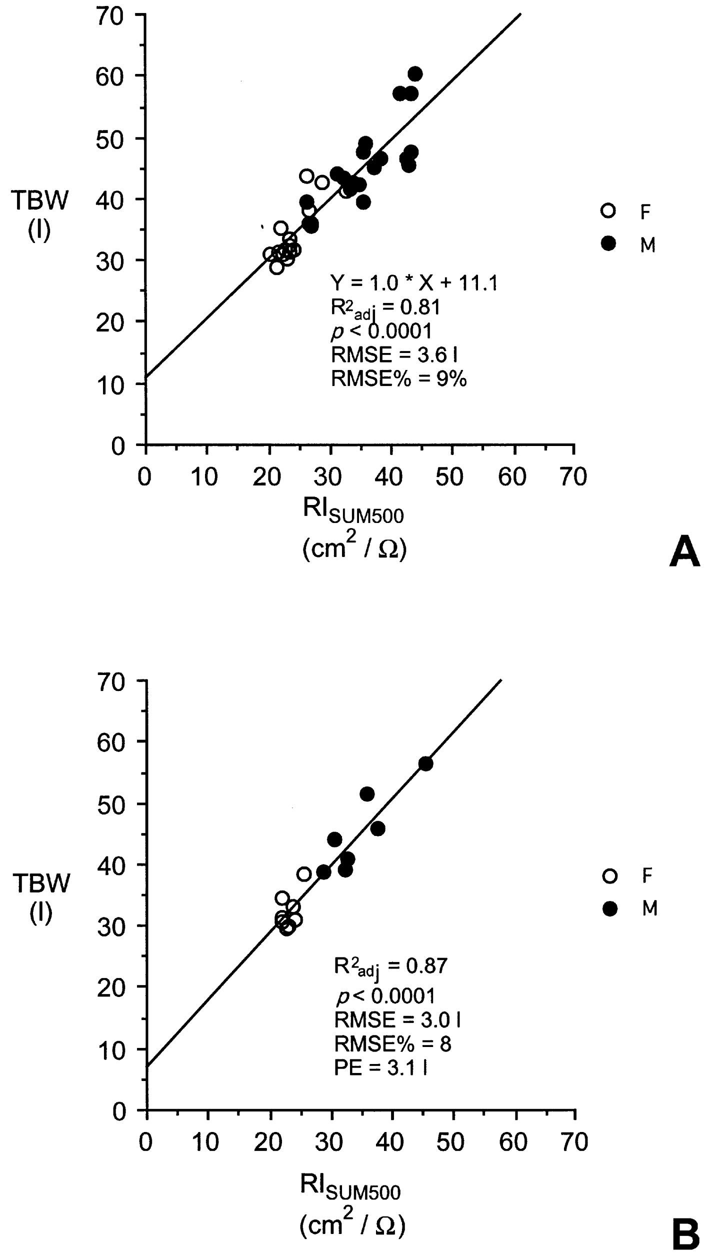

Figure 2 Random generation (A, $n=35$) and cross-validation (B, $n=15$) of a predictive algorithm for total body water from the whole-body resistance index at 500 kHz. TBW, total body water; F, female; M, male; RI_{SUM500}, resistance index at 500 kHz; RMSE, root mean square error; PE, pure error.

provide a significant advantage over traditional methods in epidemiological studies, where time constraints are very important. However, every instrument should undergo detailed studies of precision and accuracy before being employed for research and clinical purposes. Without this kind of validation, the potential advantages of a given instrument may remain just theoretical.

It is noteworthy that the right arm of the subjects had lower values of R compared to the left arm (Table 2). Because muscles are made of about 80% water (Wang *et al*, 1999) and R is inversely proportional to water, the lower R can be taken as evidence of a more developed musculature in the right arm. Even if this is in agreement with the fact that the great majority of subjects were right-handed, this hypothesis needs to be tested against direct measurements of appendicular muscle mass such as those allowed by dual-energy X-ray absorptiometry.

An important finding of this study is that R was strongly associated *by itself* with TBW, being able to explain up to 65% of its variance. These data allow us to respond to an observation raised about the role of BIA in the assessment of body composition. It has in fact been stated that, for BIA to be considered a body composition technique, associations of R—and not RI—with body compartments are to be considered (Mazess, 1991). In this study, R_{SUM500} contributed 65% of TBW variance ($P < 0.0001$, $n = 50$) and its contribution was greater than that of Ht^2 ($r^2_{\mathrm{adj}} = 0.56$, $P < 0.0001$). Moreover, when Ht^2 and R_{SUM500} were combined in the form of $\mathrm{RI}_{\mathrm{SUM500}}$, the explained variance of TBW rose to 83% ($P < 0.0001$). Thus, even if RI may not be the best descriptor of the electrical behavior of the human body on theoretical grounds, its use in predictive models is clearly worth consideration (Kushner, 1992; Kushner *et al*, 1992). This does not preclude, however, use of bioelectrical indexes other than RI, provided that they are shown to offer better estimates of body composition than RI (Organ *et al*, 1994).

Using total body Ht instead of segmental lengths as the numerator of RI did not produce substantial changes in the explained variance of TBW. Since the measurement of arm length, trunk height and leg length requires time and effort, it appears that total body Ht, which is measured with greater rapidity and precision, can safely replace segmental lengths. The most accurate and practical way of predicting TBW from eight-polar BIA is to calculate RI by dividing Ht^2 for the sum of segmental R at 500 kHz (Table 4).

We conclude that the eight-polar tactile-electrode impedance method is precise and gives accurate estimates of TBW in healthy subjects. This promising method should undergo further studies of precision and its accuracy in assessing extracellular water and appendicular body composition should be determined.

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