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Original Article

Bioelectrical Impedance Analysis in a Mathematical Model for Estimating Fat-free Mass in Multiple Segments in Elderly Taiwanese Males☆

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SUMMARY

Background: This research applied bioelectrical impedance analysis (BIA) and Dual-Energy X-ray AbsorptioMetry (DXA) to measure the body composition of Taiwan elderly. We developed the new mathematical estimation model for fat free mass of multiple segments.
Methods: The modified BIA instrument with 8 electrodes (BIA_8) at 50 kHz and 0.4 mA was used to measure the bioelectrical impedance of whole body and all limb segments of 33 male elderly in Taiwan. The criterion fat free mass (FFM) values in whole body and all limb segments were determined by DXA. After analyzing by linear regression, we obtained the FFM estimation equation for limb segments. The Bland-Altmen analysis were used to evaluate the differences existed between the estimation FFM from equation by BIA and from by DXA.
Result: The correlation efficient (R) with standard deviation (SD) of FFM measured by DXA v.s. estimated by BIA in whole body, lower limbs, upper limbs and trunk were 0.942 with 2.660 kg, 0.859 with 0.713 kg, 0.922 with 0.265 kg and 0.884 with 1.917 kg, respectively. The relative high in the weight coefficients of h^2/Z for estimation equation implied the critical role played by height and BIA values.
Conclusion: In summary, the multiple segments FFM estimated by BIA were highly relative to that of determined by DXA for elderly in Taiwan. It is feasible to apply in monitoring the body composition in elderly by fast, non-invasive and convenient way.

1. Introduction

Frailty in the elderly is often a cause of accidental falls. Sarcopenia leads to a lower appendicular muscle mass in older adults compared to the normal population[1,2]. Functional impairments in the elderly are closely related to the occurrence of sarcopenia[3]. It is a critical index in evaluating nutritional status by body composition, especially in the elderly, and is strongly related to morbidity and mortality. The fat-free mass (FFM) decreases and fat mass (FM) increases with progressive ageing[4–6].

Monitoring of malnutrition status, diseases risks and physical status by evaluating body composition is an important clinical issue in the elderly, and issues regarding accurate estimates should be addressed[7].

Many methods are used to determine body composition, including dual-energy X-ray absorptiometry (DXA), computed tomography (CT), magnetic resonance imaging (MRI), air-displacement plethysmography, underwater weighing, neutron activation analysis, and the dilution method, but each has its own limitations[8]. Owing to immobilization issues in the elderly, bioelectrical impedance analysis (BIA), which is easy to operate, non-invasive, portable and fast, is suitable for wide use in estimating body composition[9,10]. Segmental FFM measurement by DXA can be used to validate segmental BIA estimation[11].

Current estimates of body composition using BIA measurement as a foot-to-hand model include whole-body FFM, fat mass (fat %), total body weight and intercellular water. However, there are increasing clinical requirements for multiple-segment estimates[12,13],

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particularly body composition data for the upper limbs, lower limbs, and trunk[14–17]. Standing-posture BIA measurement with eight electrodes has been widely investigated, and commercial and clinical instruments are convenient and easy to use[18–21]. For commercial instruments, built-in predictive estimation equations are often not formally validated and verified, so the specific suitability for distributions in individual cohorts is in doubt. This limits the applicability of these instruments, especially in clinical settings[22]. Some verification for specific cohorts has been carried out[23]. Estimation of whole-body composition in the elderly using commercial four-electrode or eight-electrode BIA instruments has been investigated[24,25]. Measurement of sarcopenia in the elderly has been addressed as an important issue in frailty in the elderly. Validation of bioelectrical impedance for the prediction of whole-body FFM mass has been well explored, but there are very few studies on segmental FFM mass[26].

To determine equations for estimating FFM in the whole body, lower limbs, upper limbs and trunk in healthy elderly by BIA with greater precision, correlation between DXA measurements and BIA estimates using a modified instrument was investigated. Differences between the results were assessed to confirm the precision of the estimation equations.

2. Methods

2.1. Study participants

Healthy elderly (> 55 years) Taiwanese males without chronic diseases (cancer, nephrotic syndrome, hypertension, diabetes mellitus, hepatitis and related diseases, chronic pulmonary diseases), an artificial heart or assist device or any artificial electrical implantation were recruited ($n = 33$) after formal permission was granted by the Institutional Review Board (IRB) of the Advisory Committee at Jen-Ai Hospital, Taichung, Taiwan. Each individual was fully informed of the method details and steps before they formally consented to participate in the study. The consumption of alcohol (48 hours) and administration of diuretics (7 days) were restricted before experiments. Physiological characteristics are listed in Table 1.

2.2. Determination of body composition by DXA

Body weight was measured to an accuracy of 0.1 kg and body height to 0.5 cm. Each participant was dressed in cotton without any metal attachments. Whole-body DXA scans were performed using a Lunar Prodigy instrument (GE Healthcare, Madison, WI, USA) and data were analyzed using enCore 2003 Version 7.0 software. FFM, total body fat (BF) and bone mineral density were measured. The scanner was operated at 20 μGy over a period of 20 minutes by legally registered and trained medical technologists in the Department of Radiology, Jen-Ai Hospital.

2.3. Measurements with the BIA_8 instrument

The modified BIA instrument (BIA_8) we designed has independent detection and current source electrodes. After DXA measurements, BIA values were recorded for each participant while in a standing position for estimation of body composition.

A QuadScan 4000 instrument (Bodystat, Douglas, UK) was connected to a computer for automatic setting of the various measuring circuits and was operated with a current of 400 μA at a frequency at 50 kHz. The electronic impedance between two electrodes was much greater than the bioelectric impedance. To confirm that modification of the instrument did not change the accuracy or precision, data from before and after the modification were compared. As shown in Fig. 1, E1, E3, E5 and E7 were current electrodes, and E2, E4, E6 and E8 were measurement electrodes. All the electrodes were made of stainless steel with high conductivity. E1, E2, E5 and E6 were located on the handle, and E3, E4, E7 and E6 on the right side of the platform. Fig. 1 shows the circuit and measurement electrodes for bioelectric impedance of the right upper limb ($Z_{upper(R)}$), the left upper limb ($Z_{upper(L)}$), the trunk (Z_{trunk}), the right lower limb ($Z_{lower(R)}$), and the left lower limb ($Z_{lower(L)}$). $Z_{upper(R)}$, Z_{trunk}, and $Z_{lower(R)}$ are summed to calculate whole body-impedance (Z_{whole})[12]. The bioelectric impedance values for each body segment were combined with age, body height and weight parameters to develop predictive equations for body composition.

2.4. Statistical analysis

All experimental data were analyzed using SPSS.12.0 software (SPSS Inc., Chicago, IL, USA). Results are expressed as mean (± standard deviation, SD). R values obtained from linear regression analysis and Pearson correlation are presented to describe the correlation between variables. We carried out Bland–Altman analysis to compare BIA estimates and DXA results for FFM[27]. A confidence level of 5% ($p < 0.05$) was considered significant.

3. Results

The age range was 55.0–77.1 years, height was 155.0–191.3 cm, and body weight was 57.0–114.4 kg (Table 1). BF and BMI ranges measured by DXA were 6.2–40.1% and 19.8–36.8 kg/m^2, respectively (Table 1). Bioelectric impedance values (Z) for each body segment measured by BIA_8 were combined with anthropometric parameters to develop equations for estimating segmental body composition. The subscripts DXA and BIA denote the measurement technique and subscripts whole, trunk, upper and lower denote the measurement area. Thus, $FFM_{whole\text{-}DxA}$ denotes FFM measured by DXA for the whole body, and so on. The estimation equations were as follows:

$$FFM_{whole\text{-}BIA} = 15.156 + 0.652\, h^2/Z_{whole} + 0.204\, w - 0.173\, y \quad (1)$$

$$(R = 0.942,\ SD = 2.660\ kg,\ n = 33)$$

$$FFM_{lower\text{-}BIA} = 2.918 + 0.0414\, h^2/Z_{lower} + 0.052\, w - 0.045\, y \quad (2)$$

$$(R = 0.859,\ SD = 0.713\ kg,\ n = 66)$$

$$FFM_{upper\text{-}BIA} = -1.141 + 0.039\, h^2/Z_{upper} + 0.003\, w - 0.004\, y \quad (3)$$

$$(R = 0.922,\ SD = 0.265\ kg,\ n = 66)$$

$$FFM_{trunk\text{-}BIA} = 2\ FFM_{whole\text{-}BIA} - FFM_{lower\text{-}BIA(R)} - FFM_{lower\text{-}BIA(L)} - FFM_{upper\text{-}BIA(R)} - FFM_{upper\text{-}BIA(L)}\ [28] \quad (4)$$

$$(R = 0.941,\ SD = 1.876\ kg,\ n = 33),$$

where h is body height (cm), w is body weight (kg), y is age (years), Z is bioelectrical impedance (Ω), and FFM is in kg.

Table 1
Anthropometric and body composition indices for the study population ($n = 33$ males).

	Mean	SD	Range
Age (y)	61.1	4.9	55.0–71.2
Height (cm)	169.7	7.7	155.0–191.3
Weight (kg)	75.7	12.8	57.0–114.4
BMI (kg/m^2)	26.2	3.8	19.8–36.8
Whole-body fat[a] (%)	28.0	7.4	6.2–40.1

[a] Measured by DXA.

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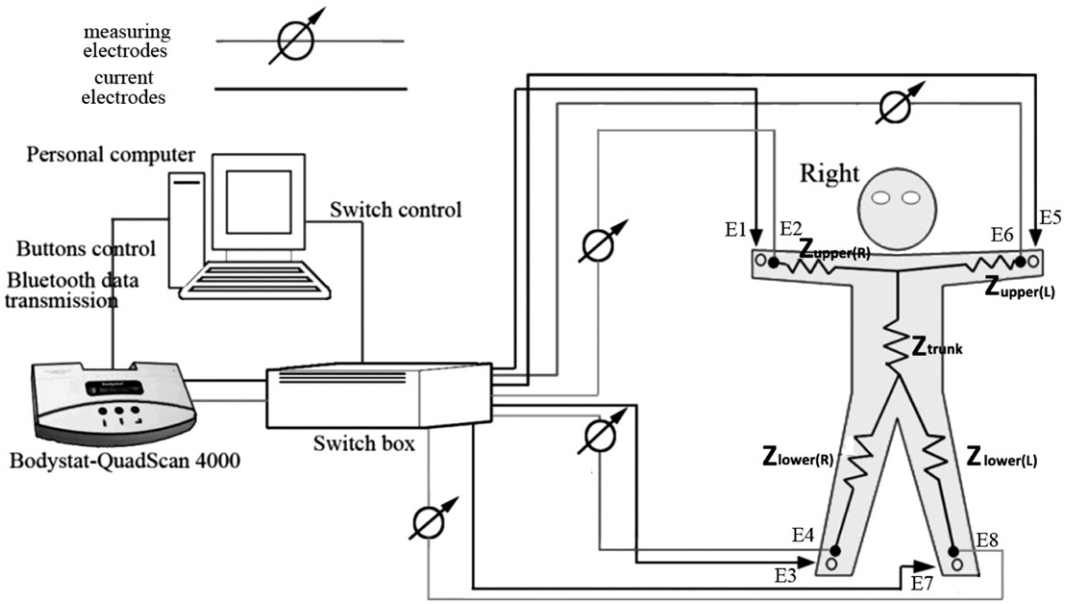

Fig. 1. The modified BIA instrument with eight electrodes (BIA_8). With a circuit between E1 and E3, measurement between E2 and E4 yields Z_{whole}, measurement between E4 and E8 yields $Z_{lower(R)}$, measurement between E2 and E6 yields $Z_{upper(R)}$ and measurement between E6 and E8 yields Z_{trunk}. With a circuit between E5 and E7, measurement between E4 and E8 yields $Z_{lower(L)}$ and measurement between E2 and E6 yields $Z_{upper(L)}$. $Z_{whole} = Z_{upper(R)} + Z_{lower(R)} + Z_{trunk}$.

$FFM_{trunk\text{-}BIA}$ was also estimated using Z_{trunk} as follows:

$$FFM_{trunk\text{-}BIA} = 10.256 + 0.002\, h^2/Z_{trunk} + 0.226\, w - 0.065\, y \qquad (5)$$

($R = 0.649$, SD = 2.162 kg, $n = 33$).

The intercept, slope, SD, and correlation coefficients for FFM measured by DXA and BIA are listed in Table 3. The correlation coefficient for whole-body FFM was relatively high, at 0.942. The correlation coefficients for lower limb, upper limb, and trunk were 0.859, 0.922, and 0.941, respectively. These coefficients confirm that BIA is relatively good in estimating FFM. Bland–Altman distributions of the variability between FFM_{BIA} and FFM_{DxA} values are shown in Fig. 2.

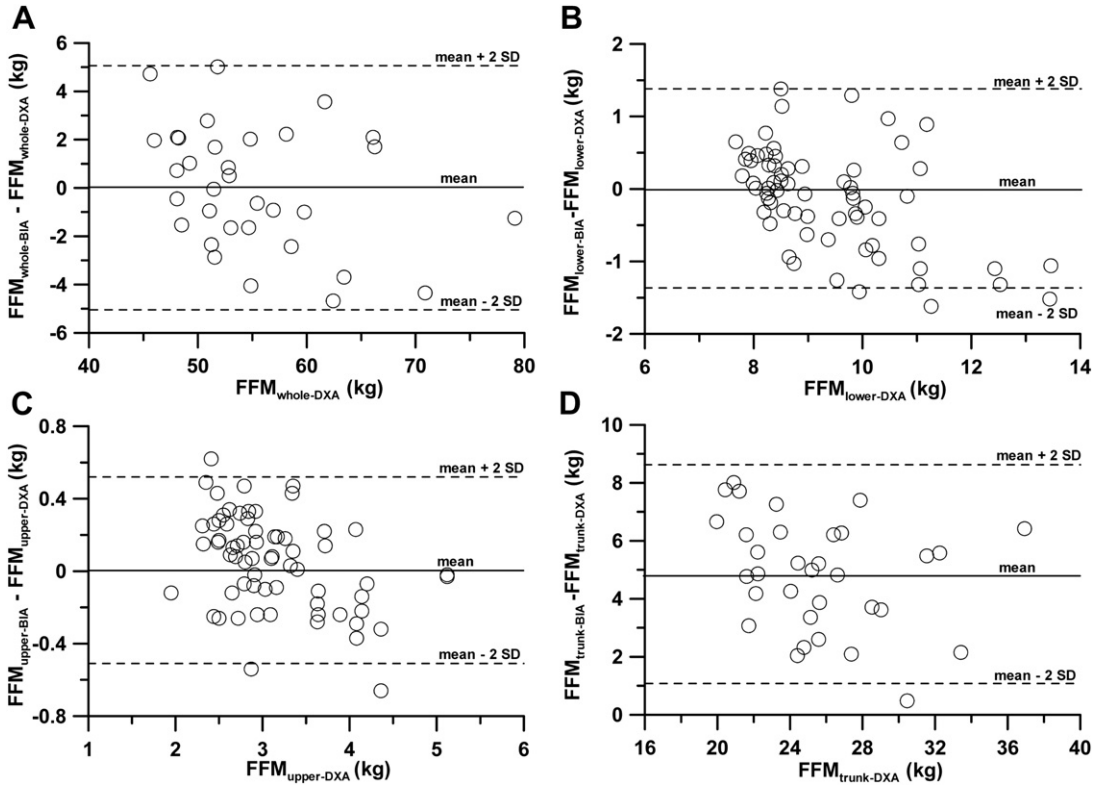

Fig. 2. Distribution plots of differences in fat-free mass (FFM) between BIA estimates and DXA results. (A) Whole-body FFM (mean = 0.0 kg, SD = 2.533 kg, mean − 2SD = −5.065 kg, mean + 2SD = 5.065 kg). (B) Lower-limb FFM (mean = 0.0 kg, SD = 0.697 kg, mean − 2SD = −1.394 kg, mean + 2SD = 1.394 kg). (C) Lower-limb FFM (mean = 0.0 kg, SD = 0.260 kg, mean − 2SD = −0.520 kg, mean + 2SD = 0.520 kg). (D) Trunk FFM (mean = 4.864 kg, SD = 1.917 kg, mean − 2SD = 1.029 kg, mean + 2SD =8.698 kg).

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The coefficients for the variables h^2/Z_{whole}, w and y in Eq. (1) are 0.652, 0.204, and −0.173, respectively (Table 2). The mean values for h^2/Z_{whole} (54.05 cm^2/Ω), w (75.8 kg) and y (61.1 years) were input into Eq. (1) obtain the $FFM_{whole} = 38.9$ kg. The percentage contributions of h^2/Z_{whole}, w, and y in Eq. (1) of 87.2%, 40.0%, and −27.1%, respectively, indicate that h^2/Z_{whole} is crucial. Similarly, the contribution of h^2/Z was 93.0% in Eq. (2) and 90.1% in Eq. (3).

4. Discussion

The modified BIA_8 instrument, with independent detection and current source electrodes in the platform and the grip handle, can generate different circuits to measure BIA values in corresponding segments by switching the measurement circuits[12]. It is well known that BIA values are highly correlated with lean body mass[29], which provides an excellent rationale for estimating body composition by BIA. Since it is assumed that the cross-sectional area is homogeneous and similar for the trunk and body segments for BIA measurements, the length and bioelectric impedance are major parameters. In many studies, h^2/Z_{whole} is used as the major independent variable. We used the same approach in Eq. (1) for FFM_{whole}. Similarly, we used h^2/Z_{lower} in Eq. (2) for $FFM_{lower\text{-}BIA}$ and h^2/Z_{upper} in Eq. (3) for $FFM_{upper\text{-}BIA}$ to determine linear regression coefficients and obtain optimal estimation equations. In fact, body height between arm segments has yielded high correlation coefficients ($R = 0.967–0.975$)[30], so it is reasonable to assume that height is constant for body segments. Notably, use of height (h) rather than upper limb and lower limb length is more convenient. There was good correlation between $FFM_{lower\text{-}BIA}$ ($R = 0.859$) and $FFM_{upper\text{-}BIA}$ ($R = 0.923$) and the corresponding DXA results. As shown in Fig. 2a and Table 3, the SD was relatively low SD (2.533 kg) and there was good correlation ($R = 0.942$) between $FFM_{whole\text{-}BIA}$ and $FFM_{whole\text{-}DxA}$. Whole-body FFM measurements in 106 elderly individuals by Genton et al[31] were compared with estimates in other studies and the results were similar to those in the present study[32–35]. In spite of minor differences between our study and that of Genton et al, the correlations and SD for FFM_{whole} were similar[27]. In addition, relatively higher differences and lower correlation coefficients ($R = 0.79 - 0.90$) were found between lower-limb FFM estimated by an anthropometric method and measured by DXA for rugby union players than in the present study. In comparison, we found relatively lower SD and higher correlation between BIA estimates and DXA measurements for the lower limbs (SD = 0.697 kg, $R = 0.859$), upper limbs (SD = 0.260 kg, $R = 0.923$) and the trunk (SD = 1.917 kg, $R = 0.884$). In previous studies, measurement of segmental FFM with high precision and accuracy has not been well addressed. Mally et al compared muscle mass estimated using a commercial instrument (BC-418 MA, Tanita, Tokyo, Japan) and measured by DXA in elderly males and found underestimation of 6–18%[25]. Segmental FFM in elderly males estimated using the equations above exhibited greater precision and accuracy.

Since $FFM_{trunk\text{-}BIA}$ obtained using Eq. (4) involves subtracting $FFM_{lower\text{-}BIA}$ and $FFM_{upper\text{-}BIA}$ from $FFM_{whole\text{-}BIA}$, it should also contain the FFM contribution of the head. Eq. (4) yielded $R = 0.941$ and SD = 1.876 kg for $FFM_{trunk\text{-}BIA}$. With a circuit between E1 and E3 with measurement between E6 and E8, Z_{trunk} was measured as 43.1 (± 11.1) Ω. This yielded a lower correlation coefficient (0.649) and greater SD (2.162 kg) when calculating $FFM_{trunk\text{-}BIA}$ using Eq. (5) instead of Eq. (4). This can be attributed to the complexity of organs within the trunk and the large cross-sectional area. The highest contribution by h^2/Z_{whole} to Eq. (1) indicates that this parameter is crucial in estimating FFM_{whole}, in agreement with results reported by Lukaski et al[36]. Similar evidence can be observed for Eqs (2) and (3).

Table 2
Whole-body and segmental FFM measured by DXA and h^2/Z values measured by BIA_8.

Parameter	Mean (SD)	Range
$FFM_{whole\text{-}DxA}$ (kg)	55.25 (7.58)	45.62–79.12
$FFM_{trunk\text{-}DxA}$ (kg)[a]	30.21 (4.00)	24.59–41.97
$FFM_{lower(R)\text{-}DxA}$ (kg)	9.50 (1.43)	7.67–13.44
$FFM_{lower(L)\text{-}DxA}$ (kg)	9.27 (1.31)	7.79–13.46
$FFM_{upper(R)\text{-}DxA}$ (kg)	3.20 (0.66)	2.41–5.12
$FFM_{upper(L)\text{-}DxA}$ (kg)	3.06 (0.69)	1.95–5.12
Z_{whole} (Ω)	539.6 (53.8)	407.7–622.0
Z_{trunk} (Ω)	43.1 (11.1)	32.1–78.2
$Z_{lower(R)}$ (Ω)	244.5 (24.5)	165.3–264.7
$Z_{lower(L)}$ (Ω)	226.4 (24.6)	175.0–275.0
$Z_{upper(R)}$ (Ω)	284.5 (25.4)	227.7–320.0
$Z_{upper(L)}$ (Ω)	294.5 (31.7)	220.0–348.0
h^2/Z_{whole} (cm^2/Ω)	54.1 (7.8)	43.9–77.9
h^2/Z_{trunk} (cm^2/Ω)	684.6 (159.6)	339.8–1009.4
h^2/Z_{lower} (cm^2/Ω)	129.4 (17.5)	104.6–174.8
h^2/Z_{upper} (cm^2/Ω)	101.0 (16.0)	69.0–151.6

[a] The $FFM_{trunk\text{-}DxA}$ value includes the head segment.

Table 3
Whole-body and segmental FFM correlation[a] between DXA measurements and BIA_8 estimates.

	R	Slope	Intercept
Whole body	0.942	0.889	6.181
Lower limb	0.859	0.732	2.376
Upper limb	0.923	0.838	0.557
Trunk	0.884	0.860	8.434

[a] Correlation is presented as the correlation coefficient R and the slope and intercept for linear regression equations.

5. Conclusions

The relatively low SD and high correlation coefficient between FFM_{BIA} estimates and FFM_{DxA} results indicate that the application is suitable for body composition monitoring in elderly males, especially for segmental FFM.

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