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Comparing the Whole Body Impedance of the Young and the Elderly using BIMS

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Abstract

The bioelectrical impedance (BI) for the young and the elderly was measured using bioelectrical impedance spectroscopy (BIS). First, while applying a current of 600 μA to the foot and hand, BI was measured at 50 frequencies ranging from 5 to 1000 kHz. The BI for young subjects was considerably lower than that for old subjects since young subjects have more lean mass (hydration). The prediction marker was 0.74 for young subjects and 0.78 for old subjects. Second, a Cole-Cole diagram was obtained for young subjects and old subjects, indicating the different characteristic frequencies. At 50 kHz, the average phase angle was 7.8^o for young subjects whereas that was 6.1^o for old subjects. Third, BIVA was analyzed for young subjects and old subjects. The vector length was 210.89 [Ω/m] for young subjects and 326.12 [Ω/m] for old subjects. At 50 kHz, the resistance (R/H) and the reactance (X_C/H) divided by height were 208.94 [Ω/m] and 28.68 [Ω/m] for young subject, and 324.33 [Ω/m] and 34.09 [Ω/m] for old subjects.

Keywords: Bioelectrical impedance (BI), Resistance (R), Reactance (X_C), Cole-Cole diagram, Phase angle (θ), Bioelectrical impedance vector analysis (BIVA)

1. INTRODUCTION

Bioelectrical impedance analysis (BIA) is a safe, practical, and non-invasive method for measuring components of biological tissues and biological materials [1-4]. BIA relies on the conduction of a radio-frequency electrical current by the fluid (water, interstitial fluid, and plasma), electrolytes, extracellular fluid (ECF) and intracellular fluid (ICF), and the permeability or conductivity of cell membranes in the body [5].

Depending on the applied frequency, BIA can be classified into single-frequency analysis and multi-frequency analysis. [6]. Single-frequency analysis is used to measure bioelectrical impedance (BI) while applying a constant alternating current (AC) to living tissues or biological samples. On the other hand, multi-frequency analysis is used to measure BI at each frequency by applying a chirp waveform in combination with multiple frequencies ranging from low-frequency (LF) to high-frequency (HF). The advantage of single-frequency analysis is that BI can be measured in over a short period of time, but the disadvantage is that BI cannot be analyzed in different frequency bandwidths [7]. In contrast, the advantage of multi-frequency analysis is that characteristics of the living tissue or biological samples can be analyzed in different frequency bandwidths. However, the measuring circuit of the multi-frequency analysis can be rather complex [8].

An impedance (Z) is obstruction to the flow of an alternating current, depending on the applied frequency. Impedance consists of resistance (R) and reactance (X_C). The R is the real part of Z; a device with purely resistive impedance exhibits no phase shift between the voltage and current. In BI, R reflects the water or fluid (hydration status) in the body. X_C is the imaginary part of the Z; a component with a finite reactance induces a phase shift between the voltage across it and the current through it.

A phase angle (θ) is a linear method of measuring the relationship between electrical R and Xc in series or parallel circuits [9]. In the healthy living body, the cell membrane consists of a layer of non-conductive lipid material sandwiched between two layers of conductive protein molecules. The R reflects the water or fluid in the body, and the Xc reflects the body cell mass. Thus, fluid and muscle mass will influence the phase angle [10]. The θ, associated with changes in cellular membrane integrity and alterations in fluid balance, has been established as a marker for

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the diagnosis of malnutrition and clinical prognosis [11]. Lower phase angles suggest cell death or decreased cell integrity, whereas higher phase angles suggest large quantities of intact cell membranes [12-13]. The θ has been found to be a prognostic marker in several clinical conditions. The bioelectrical impedance vector analysis (BIVA) represents a quick pictorial method demonstrating the hydration and nutritional status of a subject in comparison to that of their population group. The BIVA simply uses R and X_C at 50 kHz, measured in relation to the subject's height [10]. These results are represented by a dot on the vector graph. The positioning of the dot reflects the subject's health status in comparison to that of their relevant population group. BIVA systems use a fundamentally different approach to the measurement of hydration, which overcomes many of these issues. BIVA measures the patient's R and X_C values and calculates the phase angle and impedance [14]. The R component relates predominantly to water content and hydrated tissues and, in the normal healthy state, a decreased R/H correlates with body size, and may be related to edema and high water content. Similarly, a very high R may indicate dehydration and wasting [15].

In this study, BI of the whole body was measured using BIMS (MultiScan 5000, Bodystat Ltd., U.K.). The BIparameter values (Z, R, X_C, θ) were acquired as a function of frequency. The prediction marker (PM), relationship between R *and* X_C (Cole-Cole diagram), maximum X_C, R/H and Xc/H, and BIVA were obtained for young subjects and elderly subjects. Furthermore, these BI parameters (Z, R, X_C, θ, PM, Cole-Cole diagram, maximum X_C, R/H and Xc/H, and BIVA) were analyzed for young subjects and elderly subjects.

2. RESEARCH METHOD

2.1 Impedance parameters (Z, R, X_C, θ)

In BI, *Xc* reflects the body cell mass (muscle mass) in the body. The R and *Xc* together determine the magnitude and θ of the Z, given by the following equation.

$$|Z| = \sqrt{ZZ^*} = \sqrt{R^2 + X_C^2} \tag{1}$$

In a phase diagram, the angle between R and *Xc* is the θ of the source voltage (V) with respect to the current (I): that is, the θ by which the source voltage leads the current.

$$\tan\theta = \frac{X_C}{R} \text{ or } \theta = \arctan\left(\frac{X_C}{R}\right) \tag{2}$$

The phase angle θ has long been linked to nutritional status, and it is fast becoming recognized as a global health marker in total body health assessment.

The capacitor (C_m) affects the current, having the ability to stop it altogether when fully charged. Since AC voltage is applied, there is a root mean square (RMS) current, but it is limited by the capacitor. This is considered to be an effective resistance of the capacitor to AC, and so the RMS current (I) in the circuit containing only a capacitor (C) is given by another version of Ohm's law to be [16]

$$\mathrm{I} = \mathrm{V}/X_C \tag{3}$$

where V is the RMS voltage and X_C is defined to be

$$X_C = (\omega C)^{-1} = (2\pi f C)^{-1}\,. \tag{4}$$

The X_C of a capacitor is inversely proportional to both to the Cand to the angular velocity (ω); the greater the capacitance and the higher the f, the smaller the X_C [17]. The C reacts very differently at different frequencies. The C impedes low frequencies the most, since low frequencies allow them time to become charged and stop the current. If the frequency goes to zero (DC), X_C tends to infinity, and the current is zero once the C is charged. At very high frequencies, the C tends to zero it has a negligible X_C and does not impede the current.

2.2 Equivalent Circuit of Cell Membrane, ICF, and ECF

Total body water (TBW) accounts for approximately 60% of body weight depending on the age, the sex, and the body mass index (obesity) of the subject. The intracellular fluid (ICF) accounts for about 40% of TBW, extracellular fluid (ECF) about 20% of TBW. Furthermore, the interstitial fluid (ISF) occupies about 15% of ECF, the plasma about 5% of ECF. Despite having

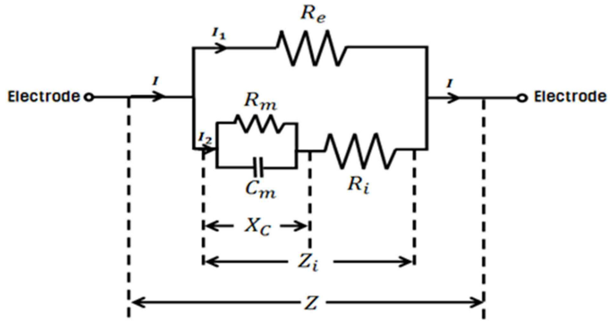

Fig. 1. Equivalent circuit of the cell membrane (C_m), ECF (R_e), and ICF (R_e).

Table 1. Meaning of symbols indicated in Fig.1

Symbol	Description
Cm	Capacitance of cell membrane
Rm	Resistance of cell membrane
Re	Resistance of ECF
Ri	Resistance of ICF
Xc	Reactance of cell membrane
Zi	Impedance of Xc and Ri(ICF)
Z	Impedance of Zi and Re (ECF)
I	Current through both ECF and ICF
I_1	Current through only ECF
I_2	Current through both cell membrane and ECF

lower protein content, the composition of ISF is similar to that of the plasma. Cells constituting human tissue consist of ECF and ICF that behave as electrical conductors, while the cell membrane acts as an electrical capacitor [18].

Fig. 1 indicates an equivalent circuit of the cell membrane, and Table 1 descriptions of indicated symbols.

Since the resistance R_m and the capacitance C_m of the cell membrane are connected in parallel, the X_C of the cell membrane in Fig. 1 can be represented by Eq. 5.

$$X_C = \frac{1}{\frac{1}{R_m}+j\omega C_m} = \frac{R_m}{1+j\omega R_m C_m} = \frac{R_m}{1+j2\pi f R_m C_m} \tag{5}$$

Impedance (Z_i) of the cell membrane and the ICF can be represented by Eq. 6.

$$Z_i = X_C + R_i = \frac{R_m}{1+j2\pi f R_m C_m} + R_i \tag{6}$$

The total impedance Z - which consists of the reactance X_C of the cell membrane, the resistance R_i of the ICF, and the resistance R_e of the ECF - can be represented by Eq. 7.

$$Z = \frac{1}{\frac{1}{Re}+\frac{1}{Z_i}} = \frac{R_e Z_i}{Re+Zi} \tag{7}$$

The reactance X_C of the cell membrane depends on the applied frequency. When the frequency is high, Z is decreased since X_C in Eq. 1 is decreased, and Z_i in Eq. 2 is also decreased. Conversely, when the applied frequency is low, Z is increased as the opposite phenomenon occurs [19].

3. RESULTS

The experimental subjects were 33 male adults consisting of two distinct groups. The young group consisted of 18 young, healthy adults with a mean age of 25.2 years (±4.7 years), an average height of 174.5 cm (±6.5 cm), and an average mass of 76.8 kg (±8.1 kg). The old group consisted of 15 subjects with a

Table 2. Measured values of impedance parameters vs. frequency for the young (N=18) and the elderly(N=15)

	f[kHz]	5	10	20	30	40	50	60	70	80	90	100
		150	200	250	300	400	500	600	700	800	900	1000
Z[Ω]	20's	452.9	442.2	419.7	403.8	391.2	379.6	370.4	365.6	360.9	357.8	354.3
		341.6	334.4	326.9	325.8	319.9	316.6	315.2	313.3	311.5	310.7	309.8
	60's	642.3	625.6	598.9	579.3	565.0	554.4	544.3	538.0	533.1	529.0	524.8
		510.5	501.0	494.2	486.9	481.0	478.2	477.1	475.1	474.2	473.5	472.8
R[Ω]	20's	452.2	440.5	416.9	400.5	387.8	376.1	367.1	362.4	358.0	354.9	351.7
		339.3	332.8	325.9	324.8	319.3	316.2	314.4	312.9	311.4	310.6	309.8
	60's	641.6	624.1	596.0	576.3	561.8	551.4	540.3	535.2	530.6	526.5	522.1
		508.2	499.4	489.9	488.2	480.3	477.7	476.1	474.8	474.0	473.4	472.7
X_C[Ω]	20's	25.3	38.5	48.2	51.3	50.6	51.5	49.6	48.4	45.9	44.6	43.2
		38.1	32.6	25.1	23.7	19.0	16.0	13.2	11.4	8.7	7.1	4.9
	60's	30.3	43.6	55.0	58.5	57.1	58.0	56.8	55.3	52.0	52.6	53.0
		44.9	40.2	30.8	30.3	25.2	22.5	19.3	16.3	13.2	10.7	7.4
θ[°]	20's	3.2	5.0	6.6	7.3	7.4	7.8	7.7	7.6	7.3	7.2	7.0
		6.5	5.6	4.4	4.1	3.4	2.9	2.5	2.0	1.6	1.3	0.9
	60's	2.7	4.0	5.3	5.8	5.8	6.0	6.0	5.9	5.6	5.7	5.8
		5.1	4.6	3.6	3.6	3.0	2.7	2.4	2.0	1.6	1.3	0.9

mean age of 65.7 years (±3.6 years), an average height of 170.5 cm (±4.3 cm), and an average mass of 60.8 kg (±4.4 kg). Prior to the experiment, the purpose and method of this study were explained to the subjects, and their consent was obtained. The study was approved by the ethics committee of InjeUniversity Institutional Review Board for Clinical Studies (Document number: 2014250).

Each measurement was performed after a 10-minute break. Body mass index (BMI) was calculated as the ratio between weight and height squared (kg^2/m^2). A tetrapolar BIA measurement of R and Xc was taken at 50 frequencies ranging from 5 kHz to 1000 kHz. The Z was measured between the right wrist and right ankle while the subject lay in a supine position on a nonconductive surface with BIMS which applies an AC 600 μA current. For this measurement, the subject must be supine with the inferior limbs at 45° and the superior limbs abducted at 30° to avoid skin contact with the trunk of the body and with the stretcher [20]. Four cutaneous electrodes (BODYSTAT – 0525, Bodystat Ltd, U.K,), two on the wrist and two on the ankle, are applied with an inter-electrode distance of at least 5 cm to prevent interaction between electrodes.

Table 2 shows the average values of impedance parameters (Z, R, X_C, and θ) versus 22 frequencies ranging from 5 to 1000 kHz for the young (N=18) and the elderly (N=15). As shown in Eq. 7, Z is reduced when the applied frequency is increased. Impedance parameter values (Z and R) for the elderly were higher than those for the young, since the elderly have more fat but less lean mass than the young. The R reflects the water or fluid (hydration state) in the body, and the X_C reflects the body cell mass (lean mass). The Xc did not show a significant difference between the young and the elderly because measured values were comparatively low in relation to Z and R. Thephase angle θ in old subjects were lower than those in young subjects and were strongly dependent on the applied frequency. At 5 kHz, the averagephase angle θ for the young subjects was 7.8° whereas that of the old subjects was 60°.

Fig. 2 shows Z as a function of the frequency (f). At 5 kHz, BI value was 642.3 Ω for old subject (#23) and 452.9 Ω for young subject (#4). Z values were considerably higher for old subject since old subjects since they have more fat and less lean mass (which consists mostly of muscles and tissues) compared to young subjects. Z values were abruptly decreased from 5 to 50 kHz at first and then gradually decreased up to 1,000 kHz. These results are in agreement with the result reported by Lukaski et al. [21]: when a low frequency (~ 5 kHz) is applied to human tissue, BI is observed to be high since the current flows through ISF.

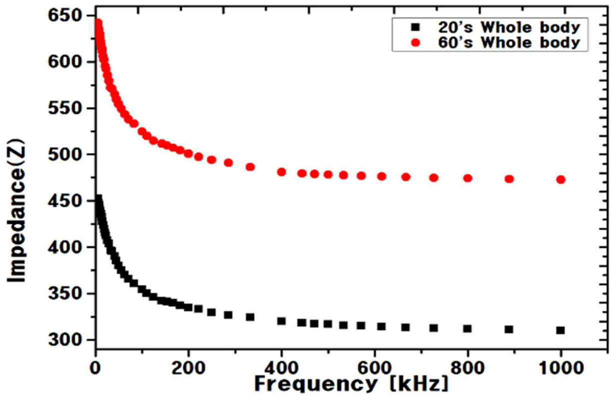

Fig. 2. Impedance (Z) vs. frequency (f) for young subject (#4) and old subject (#23).

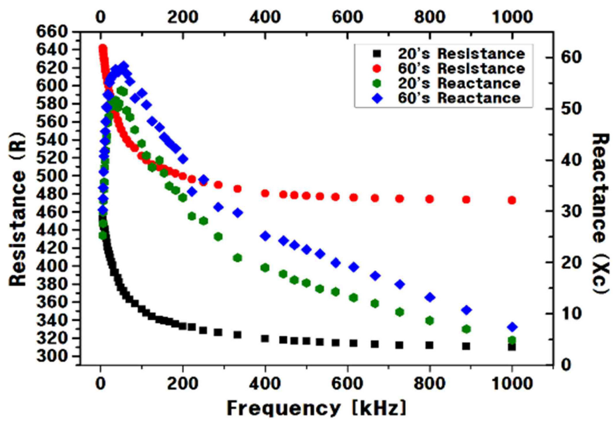

Fig. 3. Resistance (R) and reactance (X_C) vs. frequency

The PMis the ratio between the Z at 5 KHz and 200 kHz. At 5 kHz, the current cannot penetrate the cell membrane and therefore flows through in ECF (R_e) as seen in Fig. 1. However, at 200 kHz, the current is strong enough to penetrate the cell membrane and then flow through ICF (R_i) as well as ECF (R_e), as seen in Fig. 1. The greater two variances are between the two impedances at 5 kHz and 200 kHz, the healthier the body cells are. A ratio closer to 1.00 indicates poor cellular health or extreme fluid. PM was 0.74±0.03 in young subjects whereas PM was 0.78±0.04 in old subjects.

Fig. 3 shows the R and X_C as a function of frequency. Since the R accounts for about 99% of the Z, the R curves were similar to the Z curves in Fig. 2. The R was largely measured in the frequency range of 5-50 kHz since the current could not pass through the cell membrane in Fig. 1. Because a current with a frequency higher than 50 kHz passes through the cell membrane, the current passes through ICF as well as ECF. At 50 kHz, R was 376.09 Ω for subject (#4) and 551.35 Ω for old subject (#23). The right side of Fig. 3 shows X_C as a function applied frequency. The

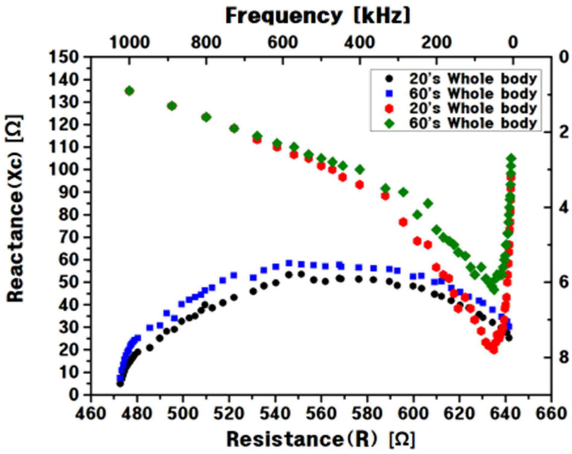

Fig. 4. Relationship between R and Xc(Cole-Cole diagram) and phase angle vs. frequency

X_C shows imaginary impedance of the cell membrane (Rm).The maximum reactance was 51.52 Ω at 50 kHz for young subject (#4) and 56.72 Ω at 56 kHz for old subject (#23). The characteristic frequency (f_c) is the frequency at which the Xc is highest. In general, when the subject is healthy, the f_c is low. When the subject is not healthy (and is old), the $f_c$moves toward a high frequency.

Fig. 4 shows the relationship between R and Xc (Cole-Cole diagram) of the whole body for young subject (#4) and old subject (#23). The values of the R and Xc were reduced as the frequency was gradually increased from 5 to 50 kHz and then gradually decreased to 1000 kHz. As the C charges or discharges, a current flows through it that is restricted by the internal resistance (capacitive reactance) of the C. The X_C varies with the applied frequency, so that any variation in supply frequency will highly effect the C, or the "capacitive reactance" value [22]. The curve of R vs. Xc for old subject (#23) was higher than that for young subject (#4). The Xc is reported to be proportional to the muscle mass and the structural integrity of cell membrane [23]. Decreases in R were reported to reflect localized fluid accumulation, and reductions in X_C [24-25].

In addition, the right side of Fig. 3 demonstrates thephase angleθ at 50 frequencies, ranging from 5 to 1000 kHz. The phase angleθ was increased from 5 to 50 kHz, and then decreased from 50 to 1000 kHz. Thephase angleθ at 50 kHz was 7.8° for young subject (#4), which was larger than the phase angle θ of 6.1° for old subject (#23). The phase angle θ is dependent on fat free mass (FFM), BMI (29.3 kg/m^2 for young subjects and 22.1 kg/m^2 for elderly subjects), and skeletal muscle (41.5 kg for young subjects and 25.2 kg for old subjects). It has been suggested that the phase angleθ could be an indicator of cellular health, where higher values reflect higher cellularity, greater cell membrane integrity, and better cell function [26].

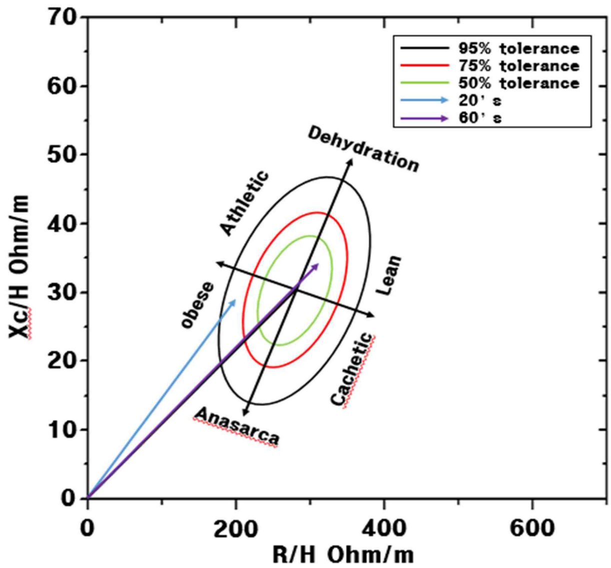

Fig. 5. BIVA for young subject (#4) and old subject (#23).

Fig. 5 shows BIVA for young subject (#4) and old subject (#23). The vector length was 210.89 for the young subject and 326.12 for the older subject. At 50 kHz, the resistance (R/H) and the reactance (X_C/H) divided by height were 208.94 [Ω/m] and 28.62 [Ω/m] for the young subject (#4), and 324.33 [Ω/m] and 34.09 [Ω/m] for the older subject. This is due to the body composition and the function of body tissues. Fat free mass (FFM) was 83.2% for young subject (#4) and 74.9 % for old subject (#23). The R component relates predominantly to water content and hydrated tissues and, in the normal healthy state, a decreased R/H correlates with body size, and may relate to edema and high water content. Similarly, a very high R in illness may relate to dehydration and wasting [15].

4. CONCLUSION

A tetrapolar BIA measurement of resistance (R) and reactance (Xc) was taken at 50 frequencies ranging from 5 kHz to 1000 kHz. Impedance was measured, between the right wrist and right ankle while the subject lay in a supine position on a nonconductive surface, by using bioelectrical impedance spectroscopy (Multi-Scan 5000, Bodystat Ltd., UK) which applied an AC 600μA current.

Impedance parameter values (Z and R) for the elderly were higher than those for the young since the elderly have more fat but less lean mass than the young. Phase angles in old subjects were lower than those in young subjects and were strongly dependent on the applied frequency. At 5 kHz, the average phase angle for the young subjects was 7.8 whereas that for the old subjects was 6.0. PM was 0.73 ± 0.03 in young subjects whereas PM was 0.79 ± 0.04 in old subjects. The relationship between resistance *R*and reactance *Xc* (Cole-Cole diagram) was obtained for young subject (#4) and old subject (#23). The maximum reactance was 51.52 Ω at 50 kHz for young subject (#4) and 56.72 Ω at 56 kHz for old subject (#23).

The phase angleθ at 50 kHz was 7.8° for young subject (#4), which was larger than that of 6.1° for old subject (#23). The phase angleθ is dependent on FFM, BMI (29.3 kg/m^2 for young subjects and 22.1 kg/m^2 for older subjects) and skeletal muscle (41.5 kg for young subjects and 25.2 kg for old subjects). The bioelectrical impedance vector analysis (BIVA) for young subject (#4) and old subject (#23) was calculated from BI measurements. The vector length was 210.89 for young subject and 326.12 for older subject. At 50 kHz, the resistance (*R*/H) and the reactance (X_C/H) divided by height were 208.94 [Ω/m] and 28.62 [Ω/m],respectively, for young subject (#4) and 324.33[Ω/m], and 34.09 [Ω/m], respectively for the older subject.

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