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Bioelectrical Impedance Analysis at the Inner Region of Forearms Using BIMS

J. H. Kim, S. H. Kim, S. S. Kim, Y. J. Kim, G. R. Jeon

***Abstract*— The bioelectrical impedance (BI) of the inner forearms was measured using bioelectrical impedance measurement system (BIMS), which employs the multi-frequency and the two-electrode method. Experiments were performed as follows. First, while applying a constant current of 800 µA to the inner region of forearms, BI was measured at eight different frequencies ranging from 10 to 500 KHz. When a current having a frequency larger than 50 KHz was applied to forearms, BI was significantly reduced. Second, the relationship between reactance and resistance was obtained using BIMS. The phase angle was strongly dependent on the applied frequency. At 50 KHz, the maximum phase angle of the right forearm was 8.2˚ slightly larger than 8.1˚ of the left forearm. Third, BI values of ECF and ICF were calculated by utilizing the multi-frequency bioelectrical impedance analyzer (BIA). At 10 KHz, BI values of ECF in the left and right forearm were 1553.58 Ω and 1533.42 Ω, respectively. It was also observed that BI values of ECF and ICF were gradually decreased when the frequency was increased from 50 KHz to 500 KHz. Logarithmic plot of BI vs. frequency shows that BI of ICF was noticeably decreased at high frequency above 300 KHz. This is due to the large decrease in the cell membrane capacitance from 300 kHz or more.**

***Index Terms*—Bioelectrical impedance, Impedance analyzer, Resistance (R), Reactance (X_C), Phase angle (θ), Extracellular fluid (ECF), Intracellular fluid (ICF), Capacitance (Cm) of cell membrane**.

I. 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 radio-frequency electrical current by the fluid (water, interstitial fluid, and plasma), electrolytes, and permeability or conductivity of cell membrane in the body [5].

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

Many studies on BIA have been carried out in order to analyze the composition of living tissue or biological samples [9-14]. Deurenberg et al. [9] examined the application of BI method to measure the composition changes in the human body. Kushner et al. [10] utilized BIA to determine the extracellular water (ECW) and total body water (TBW) in a normal human body. Scheltinga et al. [11] measured the electrical resistance across the whole body and its various segments before and after the intravenous injection of 1000 ml of saline. They found that BIA could detect minimal alterations in volume of body fluid. Miyatani et al. [12] investigated the validity of BI and ultrasonographic methods in predicting the muscle mass of upper arm. Norman et al. [13] reported that bioelectrical impedance vector analysis had shown to provide information about hydration and body cell mass and therefore allowed assessment of patients in whom calculation of body composition fails due to altered hydration. Furthermore, Kim et al. [14] developed a bioelectrical impedance measurement system (BIMS) with multi-frequency analysis method and two electrode method for measuring BI of body segments.

In this study, BI at the inner region of forearms was measured using BIMS with multi-frequency analysis and two-electrode method. Experimental procedure was as follows. First, BI was measured at eight different frequencies ranging from 10 to 500 KHz after attaching an in-planar (IP) electrode to the inner region of forearms. When frequency larger than 50 kHz was applied to forearms (left and right), BI was significantly decreased. Second, the relationship between reactance (X_C) and resistance (R) was acquired from experimental data, indicating a strong dependence of phase angle (θ) on the applied frequency. Third, BI values of ECF and ICF were computed using multi-frequency BIMS. BI values of ECF and ICF were rapidly decreased from 10 to 50 KHz and then gradually decreased up to 500 KHz. From a logarithmic plot of BI vs. frequency for ECF and ICF, BI of ICF was remarkably reduced at 300 KHz or more. This is in good agreement with the report [15] that the capacitance of cell membrane is considerably reduced at high frequencies.

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J. H. Kim, Computer simulation, Inje University, Gimhae-si, Korea, +82-10-9706-7377, (e-mail: rich_tree@naver.com).
S. H. Kim, Interdisciplinary of Biomedical Engineering, Pusan National University, Yangsan-si, Korea, +82-10-6591-9873., (e-mail: fassion7@nate.com).
S. S .Kim, Interdisciplinary of Biomedical Engineering, Pusan National University, Yangsan-si, Korea, +82-10-6333-9176., (e-mail: nicesusungx@nate.com).
Y. J. Kim, School of Medicine, Anesthesiology and Pain Medicine, Inje University, Busan, Korea, +82-10-4586-4751., (e-mail: anesky@inje.ac.kr).
G. R. Jeon, School of Medicine, Biomedical Engineering, Pusan National University, Yangsan-si, Korea, +82-10-3582-7534., (e-mail: grjeon@pusan.ac.kr).

II. Research Method

A. Equivalent Circuit of Cell Membrane, ICF, and ECF

Total body water (TBW) occupies 60% of the weight depending on the age, the sex, and the obesity. The intracellular fluid (ICF) accounts for about 40% of TBW and the extracellular fluid (ECF) about 20% of TBW. Further, the interstitial fluid (ISF) occupies about 15% of ECF and the plasma about 5% of ECF. Despite having lower protein content, the composition of ISF is similar to that of the plasma. Cells constituting the human organ consist of ICF and ECF that behave as an electrical conductor, while the cell membrane acts as an electrical capacitor [16].

Fig. 1 indicates an equivalent circuit of the cell membrane and Table 1 gives a description of the indicated symbols.

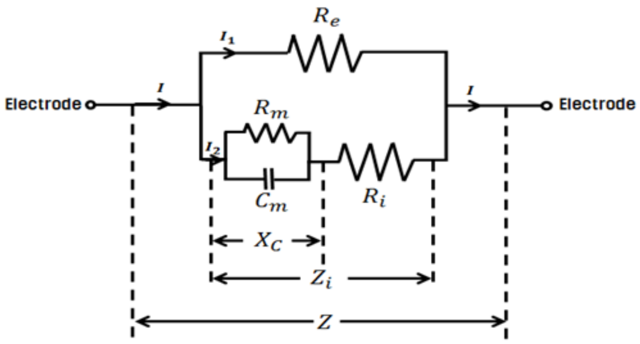


Fig. 1. Equivalent circuit of cell membrane (C_m), ECF (R_e), and ICF (R_i).

Table 1. Descriptions of symbols 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 & ICF
I_1	Current through only ECF
I_2	Current through both cell membrane and ECF

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

$$X_C = \frac{1}{\frac{1}{R_m} + j\omega C_m} = \frac{R_m}{1 + j\omega R_m C_m} = \frac{R_m}{1 + j2\pi f R_m C_m} \quad (1)$$

Impedance (Z_i) of the cell membrane and the ICF can be represented by Eq. 2:

$$Z_i = X_C + R_i = \frac{R_m}{1 + j2\pi f R_m C_m} + R_i \quad (2)$$

The total impedance Z - which consists of the reactance of the cell membrane X_C, the resistance of the intracellular fluid R_i, and the resistance of the extracellular fluid R_e - can be represented by Eq. 3:

$$Z = \frac{1}{\frac{1}{R_e} + \frac{1}{Z_i}} = \frac{R_e Z_i}{R_e + Z_i} \quad (3)$$

The reactance of the cell membrane X_C 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. Vice versa, when the applied frequency is low, Z is increased as the opposite phenomenon occurs.

B. Bioelectrical Impedance Measurement System

Bioelectrical impedance measurement system (BIMS) was described in detail in our previous paper [14]. BIMS was composed of a main control unit (MCU, ATmega128, NewTeC Co., Korea), multi-frequency generation (MFG) unit, automatic gain control (AGC) unit, constant current source (CCS), in-planar (IP) electrode, preprocessing part, and PC. MCU outputs the control command with respect to the frequency generated by MFG, and controls the overall function of BIMS. Frequencies of 10, 50, 100, 150, 200, 300, 400, and 500 KHz are generated in the MFG unit. The output voltage of frequency generated by MFG is automatically controlled in AGC unit. Constant AC current of 800 µA is generated in CCS. While the current flows into the inner region of the forearms, the segmental BI is measured and then transferred to PC after preprocessing.

PC program was developed using LabVIEW (LabVIEW 2010, National Instruments Co., USA) to control BIMS and analyze the measured BI values. PC program was configured to set parameters such as the starting frequency, the incremental frequency range, the frequency setting number, and the output voltage. Measured BI was displayed in the form of bode plot and tables and then stored in PC.

III. Result

The experimental subjects were ten male adults with a mean age of 27.5 years (±2.5 years), average height of 173 cm (±3.2 cm), and average mass of 75 kg (±4.1 kg). Each experiment was conducted five times for 10 subjects using BIMS. Each measurement was performed after a 10-minute break. Prior to the experiment, the purpose and method of this study were explained to the subjects, and their consents were obtained.

BI was measured using multi-frequency BIMS with two-electrode method. Ag/AgCl electrode (Monitoring electrode, 3M Co., USA) was used for in-planar (IP) electrode. Eight different frequencies generated from MFG unit were sequentially applied to IP electrode attached to the inner region of left and right forearm through AGC and CCS. Then, a constant current of 800 uA at each frequency ranging from 10 to 500 KHz was applied.

Fig. 2 shows BI as a function of the frequency (f) and energy (eV), when IP electrode with separation of 7 cm was positioned on the forearms. At a frequency of 10 KHz, BI values at the left and right forearms were 1560 Ω and 1540 Ω, respectively. BI were abruptly decreased from 10 to 50 kHz and then gradually decreased up to 500 KHz. These results are in good agreement with the result reported by Lukaski et al. [17]: when a low frequency (~ 10 KHz) is applied to the human tissue, BI is observed to be high since the current flows through ISF. When a medium frequency (10 ~ 50 KHz) is applied to the human tissue, the impedance is slightly lower since the current flows mainly through ECF (ISF and plasma). When a high frequency (50 ~ 500 KHz) is applied to the human tissue, the impedance is very low because the current flows through both ECF and ICF. It is interesting to note that BI of the right forearm was slightly lower than that of the left forearm. This is because nine out of ten experimental subjects were right-handed (with greater muscle mass on the right side of the forearm).

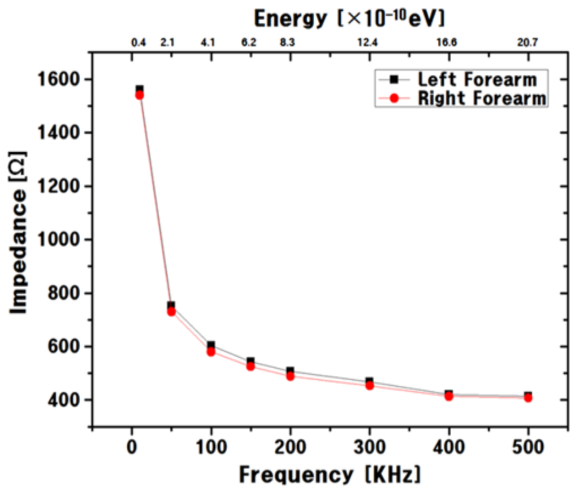


Fig. 2. Plot of BI vs. frequency at left and right forearm.

Fig. 3 shows the relationship between resistance and reactance of forearms (left and right). The values of the resistance and reactance were reduced as a frequency was increased from 10 KHz to 500 KHz. The curve of resistance vs. reactance measured at the right forearm is slight higher than that at the left forearm. This is because muscle mass and cell membrane integrity at the right forearm are higher compared to those at the left forearm. Reactance is reported to be proportional to the muscle mass and the structural integrity of cell membrane [18]. Decreases in R were reported to reflect localized fluid accumulation, and reductions in X_c [19].

In addition, plot of phase angle vs. frequency in Fig. 3 (right side) illustrates the phase angle θ between the resistance and the reactance of forearms from 10 to 500 KHz. The phase angle θ increased significantly between 10 and 50 KHz, and then was gradually reduced from 50 to 500 KHz. The phase angle θ at the right forearm was slightly larger than that at the left forearm. The phase angles θ measured at the left and right regions of the forearm at 50 KHz were 8.1°and 8.2°, respectively. Phase angle θ has been suggested to be an indicator of cellular health, where higher values reflect higher cellularity, greater cell membrane integrity and better cell function [20].

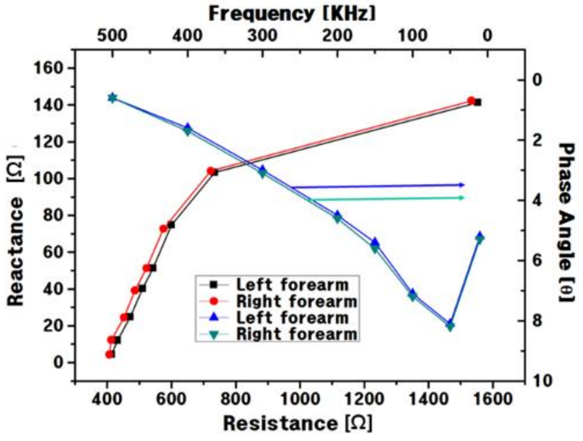
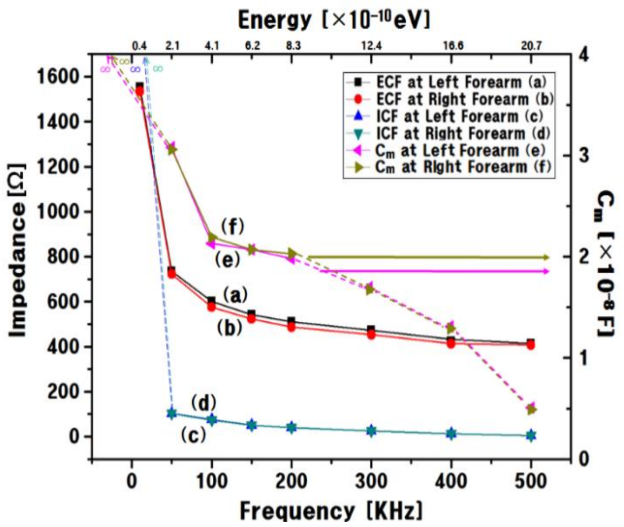


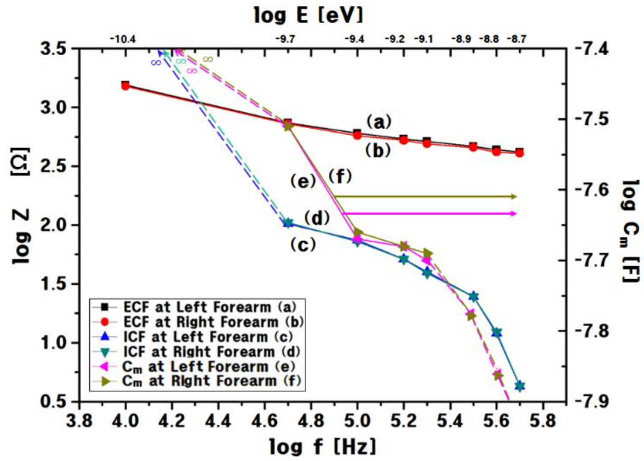
Fig. 3. Resistance, reactance, and phase angle obtained using BIMS.

Fig. 4 (a) shows BI values of forearms as a function of frequency and energy (eV). These values were decreased as the frequency was increased from 10 to 500 KHz. BI values of ECF and ICF were calculated using multi-frequency BIMS. At 10 KHz, BI values of ECF in the left and right inner forearms were 1553.58 Ω and 1533.42 Ω, respectively. BI of ECF was rapidly decreased from 10 to 50 KHz, and then gradually decreased from 50 to 500 KHz. It was estimated that BI values of ICF at 10 kHz was approaching large values because the current could flow partially through the cell membrane. For example, a current of 10 KHz has an energy of 4.14×10^{-11}eV, which is lower than potential threshold (2.05×10^{-10}eV) of the ion (Na+) channel in the cell membrane. However, BI of the ICF was rapidly decreased when the frequency was increased from 10 to 50 KHz. A current of 50 KHz has an energy of 2.10×10^{-10}eV, which is greater than potential threshold 2.05×10^{-10}eV of ionic channels in the cell membrane. Curves (e) and (f) in Fig. 4 (a) represent capacitance Cm as a function of frequency. Cm values of the cell membrane were calculated by substituting BI values of ICF and the applied frequency to equation proposed by Cornish et al. [21]. The values of Cm at 300, 400, and 500 KHz indicated by dotted lines in Figure 4 (a) were determined by curve-fitting method.

Fig. 4 (b) illustrates a logarithmic plot of ECF and ICF as a function of applied log frequency (Hz) and log energy (eV). Curve (a) and (b) represents BI values of ECF measured at the forearms. These values decreased with increasing frequency, but the slopes were a bit different at 50 KHz. The slight variation in the slopes indicates that BI of ECF shows different behavior in impedance phenomena before and after 50 KHz. Curve (c) and (d) represents BI values of ICF. These values rapidly decreased from 10 to 50 KHz and gradually decreased from 50 to 200 KHz, and then rapidly decreased from 300 to 500 KHz. This shows that BI values of ICF exhibit different behavior in the impedance phenomena before and after 50 KHz. Curves (e) and (f) in right side of Fig. 4 (b) represent log capacitance Cm as a function of log frequency (plot of frequency vs. capacitance in log scale).



(a)



(b)

Fig. 4 (a) Plot of BI (ECF, ICF, C_m) vs. frequency (energy), (b) Plot of log BI (ECF, ICF, C_m) vs. log frequency (energy).

IV. CONCLUSION

While applying a constant AC current of 800 μA to the inner region of forearms, BI was measured at eight different frequencies ranging from 10 to 500 KHz using BIMS with multi-frequency and IP electrode. The distance between IP electrodes attached to the inner region of the forearms in the body was 7 cm.

Experimental results were as follows. First, BI was measured at eight frequencies ranging from 10 to 500 KHz using BIMS. Experimental results indicated that BI was rapidly decreased from 10 to 50 KHz and then gradually decreased from 50 to 500 KHz. Second, the relationship between resistance and reactance was obtained with respect to the frequency. The curve of the resistance vs. reactance measured at the right forearm was slight higher than that at the left forearm. The phase angle θ was strongly dependent on the applied frequency. At 50 KHz, the phase angle θ at the right forearm was 8.2°, which was slightly larger than 8.1° at the left forearm. This is due to the fact that nine of 10 subjects were right-handed, with greater muscle mass and better cell membrane integrity in the right forearm. Third, BI values of both ECF and ICF were rapidly decreased from 10 to 50 KHz and then gradually decreased from 50 to 500 KHz. Logarithmic plot of BI vs. frequency reveals that BI of ICF was greatly reduced. This is because as the applied frequency surpasses 300 KHz, the capacitance of the cell membrane is considerably decreased.

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