Multi-frequency bioelectric impedance at the segments of the human body according to the distance between IP electrodes

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

***Abstract*— To measure the bioelectrical impedance at the segments of the body, multi-frequency bioelectrical impedance measurement system (BIMS) with two-electrodes was implemented in this study. The BIMS was composed of constant current source, automatic gain control, and multi-frequency generation units. Three experiments were performed using the BIMS. First, to evaluate the performance of the BIMS, bioelectrical impedance (BI) was measured by applying multi-frequency current to each circuit after composing two RC circuits, and BI measured by the BIMS was compared to BI obtained by a commercial impedance analyzer (4193A, HP. Corp., USA). Second, BI was measured using BIMS when two IP electrodes with a distance of 7 cm were positioned on the left and right forearm and at the popliteal region in the body. Third, BI was measured at each frequency ranging from 10 to 500 KHz with BIMS when the distance between two in planner (IP) electrodes was changed to 3, 5, and 7 cm. BI values of measured ECF and estimated ICF in the right forearm were also acquired. BI of ECF decreased differently according to the distance between IP electrodes, but BI of ICF sharply decreased without BI dispersion according to the distance.**

***Index Terms*— Bioelectrical Impedance, Impedance Analyzer, Multi-frequency Impedance Meter, Extracellular Fluid (ECF), Intracellular Fluid (ICF).**

I. INTRODUCTION

Bioelectrical impedance analysis (BIA) is a noninvasive method of measuring components of biological tissues and biological samples with ease [1] - [4]. There are two methods for measuring bioelectrical impedance (BI): the two-electrode and the four-electrode method. Nowadays, the four-electrode method has been used to overcome the interference problems occurring at the interface between the electrode and the skin. The two-electrode method is widely used to measure BI because the circuit for measuring BI is simple compared to that of the four-electrode method.

BIA is divided into single-frequency analysis and multi-frequency analysis depending on the applied frequency [5]. Single-frequency analysis is the method of measuring BI while applying single-frequency to living tissues and biomaterials. By contrast, multi-frequency analysis is the method of measuring BI at each frequency after applying the chirp waveform in combination with multiple frequencies ranging from low-frequency (LF) to high-frequency (HF). Further, the method of measuring BI at each frequency has also been accomplished by selectively applying a constant AC current with the frequency in the range of LF, middle-frequency, and HF. The single-frequency analysis method has the advantage that BI can be measured in a short period of time when characteristic of living tissue and biological sample is analyzed in a particular frequency bandwidth. However, the single frequency analysis has the disadvantage that BI cannot be analyzed in different frequency bandwidths [6]. On the other hand, the multi-frequency analysis method has advantage that characteristic of living tissue or biological sample can be analyzed in various frequency bandwidths. However, the multi-frequency analysis method also has disadvantage: the measurement time is long compared to that of single-frequency method, and the measurement circuit is complicated [6].

Studies on BIA have been carried out by many researchers to analyze the composition of living tissue and biological material [7] - [13]. Deurenberg et al. [7] investigated the applicability of BI for determining the changes in body composition. Hoffer et al. [8] announced that the resistance of the human body to the conduction of an alternating electrical current was related to the volume of fluid within the body. Kushner et al. [9] utilized BIA to determine the extracellular water (ECW) and total body water (TBW) content in human body. Scheltinga et al. [10] measured the electrical resistance across the whole body and its various segments before and after the intravenous administration of 1000 ml of saline. They reported that BIA was an effective method for determining minimal alterations in body fluid volume. Miyatani et al. [11], [12] investigated the validity of BI and ultrasonographic methods for predicting the muscle volume of the upper arm. Jeon et al. [13] reported on a detection system for measuring blood pressure and blood flow variation rate using the impedance method.

In addition, Thomasset et al. [2] conducted the method for determining body impedance based on the conduction of an applied electrical current in the organism. Chumlea et al. [14] analyzed the distribution of intracellular fluid (ICF) and extracellular fluid (ECF) within tissues in human body. Kanai et al. [15] analyzed the distribution of ICF and ECF in the body tissues. Lorenzo et al. [16] announced that while LF current was being applied to human tissue, BI was high because LF current flew outside the cell, rather than passing through the cell membrane. When HF current was applied to human tissue, BI decreased because HF current flew in the inner cell. In other words, ECF was determined from BI

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measured by applying LF current, TBW was measured by applying HF current, and ICF was estimated by subtracting HF impedance value from LF impedance value [17], [18].

In this paper, multi-frequency bioelectrical impedance measurement system (It will be referred to the BIMS) with two-electrode method was implemented. Further, to evaluate the possibility of clinical applications, three experiments were performed as follows: First, after configuring two kinds of RC circuits, BI was measured with the BIMS and commercial impedance analyzer (4193A, HP. Co., USA, it will be referred to the CIA). The experimental results measured by the BIMS were in good agreement with those obtained with the CIA. Second, after attaching in-planar (it will be referred to IP) electrode to the left and right forearm and the popliteal region in human body, BI was measured at eight frequencies ranging from 10 to 500 KHz with the BIMS. Third, BI values were measured at the right forearm at each frequency ranging from 10 to 500 KHz when the distance between IP electrodes was increased from 3 to 7 cm in 2-cm intervals. BI of ECF was obtained at each frequency using the BIMS, and BI of ICF at each frequency was calculated by subtracting BI of ECF measured at 500 KHz from BI measured at each frequency ranging from 50 to 500 KHz.

BI of ECF was high at 10 KHz and then decreased gradually up to 500 KHz. In other words, AC current with 10 KHz could not pass through the cell membrane because the current of 10 KHz has the energy of 0.04 eV but the cell membrane has the potential barrier (i.e., ionic selective channels) around 0.20 eV. BI of ICF sharply decreased at frequencies above 300 KHz. This is due the fact that the capacitance of the cell membrane rapidly decreased above 300 kHz, showing an increase of current in ICF with increasing frequency.

II. Research Method

A. An Equivalent Circuit of Human Body Impedance

Cells constituting human organ consist of ECF and ICF that behave as electrical conductors and cell membrane that acts as an electrical capacitor [19]. BI of human tissue is measured differently depending on the applied frequency of AC current. AC current flows outside the cell membrane when LF current is applied to human tissue, whereas AC current flows into the cell through the cell membrane, as well as outside the cell, when HF current is applied to human tissue [2], [19]. That is, when the current with LF less than 10 KHz is applied to the cells, the current only flows in the interstitial fluid (i.e., ECF), but when the current with HF above 50 KHz is applied to the cells, the current flows in both ECF and ICF. This phenomenon occurs because ECF acts as an electrical conductor in the LF bandwidth, ICF acts as an electrical conductor in the HF bandwidth, and the cell membrane acts as a type of capacitor filled with dielectric substance [20].

The capacitor is affecting the current, having the ability to stop it altogether when fully charged. Since an 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_{rms}) in the circuit containing only a capacitor C is given by another version of Ohm's law to be [21]

$$\mathrm{I} = \frac{V}{X_C} \tag{1}$$

where, V is the RMSs voltage and X_C is defined to be

$$X_C = \frac{1}{2\pi f C} \tag{2}$$

where, X_C is called the capacitor reactance, because the capacitor reacts to impede the current. X_C has a unit of ohm. X_C is inversely proportional to the capacitance C; the larger the capacitor, the greater the charge it can store and the greater the current that can flow. It is also inversely proportional to the frequency f; the greater the frequency, the less time there is to fully charge the capacitor, and it impedes current less. The capacitor reacts very differently at two differently frequencies. Capacitors impede low frequencies the most, since low frequency allows them time to become charged and stop the current. Although a capacitor is basically an open circuit, there is the RMS current in a circuit with an AC voltage applied to a capacitor. This is because the voltage is continuously reversing, charging and discharging the capacitor. If the frequency goes to zero, X_C tends to infinity, and the current is zero once the capacitor is charged. At very high frequencies, the capacitor's reactance tends to zero-it has a negligible reactance and does not impede the current [21].

The equivalent circuit in Fig. 1 was proposed to analyze BI of human tissue [22]. The circuit in the top-right corner in Fig. 1 represents BI of the interface between the electrode and the gel. E_{hc} indicates a half-cell potential, C_d and R_d are the capacitor and resistor, respectively. R_s is the impedance of skin. The central figure on the right illustrates the capacitor and resister that represent BI components in the sweet glands and the duct of epidermis. R_u at the lower right represents the resistance in the skin and subcutaneous layer.

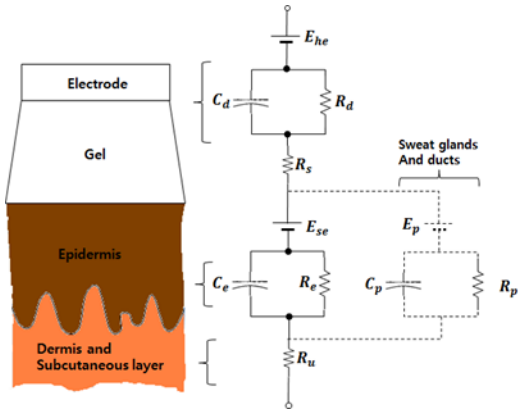


Fig. 1. The equivalent circuit of the electrode and the skin proposed for measuring BI.

B. Impedance Measurement System

As shown in Fig. 2, the BIMS is composed of a main control unit (MCU, ATmega128, ATMEL Co., Korea), multi-frequency generation (MFG) unit, automatic gain control (AGC) unit, constant current source (CCS), IP electrodes, preprocessing part, and PC. The function of these units in Fig. 2 is as follows. MCU outputs the control command with respect to the frequency that MFG is to generate, and controls the overall function of the 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 the MFG is automatically controlled in the AGC unit. Constant AC current of 500 μA is generated in the CCS part, where the current is to be output to the electrode. The body segmental BI is measured while the current applied from two electrodes attached to the body is flowing into BI measuring region. BI measured at the body segmental is transferred to the PC after preprocessing.

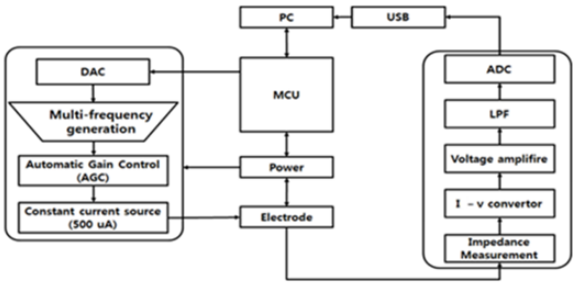


Fig. 2. BIMS configuration.

C. Multi-Frequency Generation Unit

Sine waves having multi-frequency should be applied to human tissue in order to measure the impedance in the body segment. It is possible to measure ICF, total body water (TBW), and ECF when multi-frequency is applied to the human body. Accordingly, eight types of multi-frequencies (i.e., 10, 50, 100, 150, 200, 300, 400, and 500 KHz) were generated using a frequency generating device (FGD, XR-2206, EXAR Co., USA).

The process of generating multi-frequency in the FGD is as follows. A control command from the MCU is output to a digital analog converter (DAC, DAC0800, Texas Instruments, Inc., USA). The control command has different values according to multi-frequency. These digitalized values are converted to analog values in the DAC. The analog values are output to the FGD. Input analog values are transferred to voltage converter oscillator (VCO) included in the FGD. Eight types of frequency are generated according to input voltage values in the VCO. Eight types of multi-frequency generated from the FGD were sequentially applied to the measurement regions of the human body.

D. Automatic Gain Control Unit

The output signal of the MFG is automatically controlled in the AGC unit, which adjusts the amplification rate of the output signal of the MFG. When the AGC circuit is not used, experimental errors occur in the measured impedance because the output voltage fluctuates. The circuit of the AGC is designed to maintain a constant output voltage according to the selected multi-frequency. Since the output is current, it is converted to a voltage by a voltage follower circuit.

E. Constant Current Source

In order to measure the body composition such as ECF, the cell membrane, ICF, TBW, and body fat of living tissue, a constant AC current with a frequency ranging from LF to HF should be applied to the body. In this study, a constant AC current of 500 uA was applied to the human body to measure BI at the body segments.

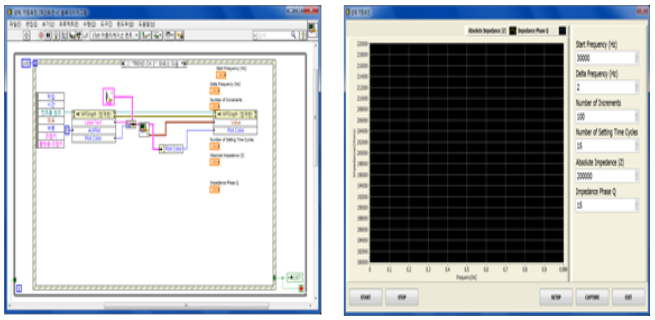
From Millman's theorem, the output voltage V_{out} is obtained from amplifying the input voltage V_{in} according to Eq. 3. When output voltage V_{out} is applied to the load resistor, R_L, constant current I_S flows according to Ohm's law.

$$V_{out} = \left(\frac{\frac{R_4}{R_1+R_4}}{\frac{R_2}{R_2+R_3} - \frac{R_1}{R_1+R_4}} \right) V_{in} \quad (3)$$

$$I_{out} = \frac{V_{out}}{R_L} \quad (4)$$

F. PC Program for measuring Bioelectric Impedance

PC program was developed using LabVIEW 2010 (National Instruments Co., USA) to control the BIMS and to analyze the measured BI data. PC software was programmed to set parameters such as starting frequency, frequency increment value, the number of increase, and the output voltage. The measured BI was displayed in the form of graphs and tables on the monitor and then stored in the PC using USB communication protocols.



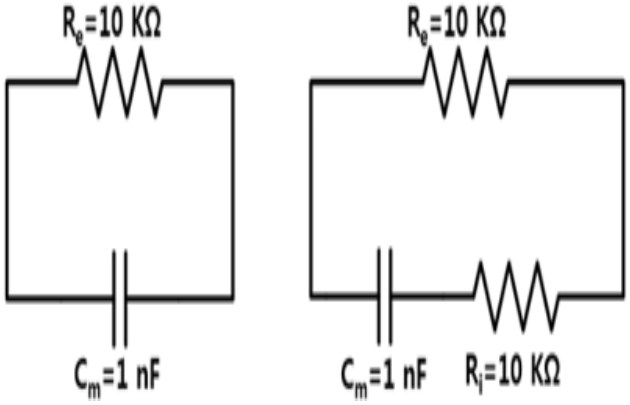
(a) (b)

Fig. 3. PC software and monitoring screen programmed for bioelectrical impedance (BI) measurement: (a) configuration of PC software using LabVIEW 2010, (b) monitoring screen.

III. Result

A multi-frequency BIMS with two-electrode method was implemented for measuring BI of the body segments. An Ag/AgCl electrode (3M Co., USA) commercialized for ECG measurement was used for in-planar (IP) electrode. Eight different frequencies generated from the MFG unit were sequentially applied to IP electrode attached to the body surface through the AGC and CCG. A constant AC current of 500 uA was set to be supplied to the body surface at each frequency ranging from 10 to 500 KHz.

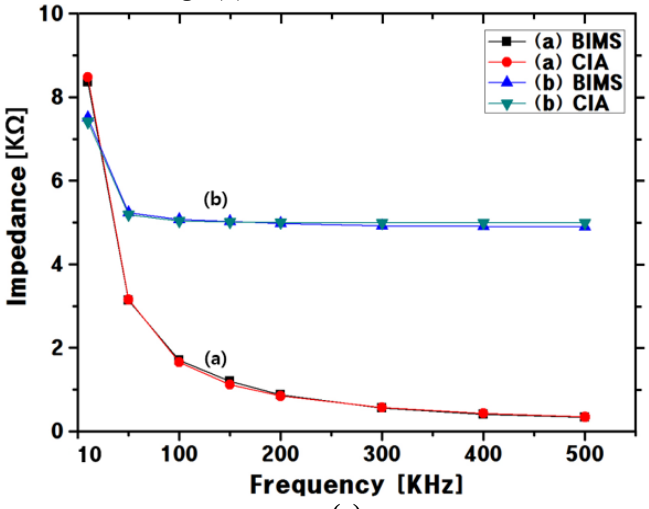
In order to evaluate the performance of the multi-frequency BIMS, experiments were carried out 10 times using the BIMS and CIA. Fig 4(a) and (b) show the equivalent circuits for biological tissues: Cell may be modeled as a group of electronic components. The extracellular fluid (ECF) is represented as a resistor (R_e), and the intracellular fluid (ICF) and the cell membrane is represented a resistor (R_i) and capacitor (C_m) [23].



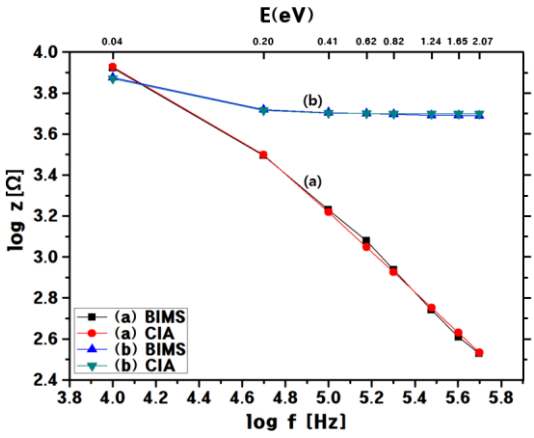
(a) (b)

Fig. 4. RC circuits suggested for impedance measurement: (a) R_e and C_m connected in parallel, (b) C_m and R_i connected in series and then connected in parallel with R_e.

Fig. 5(a) shows BI at eight frequencies ranging from 10 to 500 KHz using the BIMS and CIA while applying a constant AC current of 500 μA to the RC circuits suggested in Fig. 4. Curves (a) in Fig. 5(a) indicate BI for the circuit suggested in Fig. 4(a), which decrease almost exponentially as the frequency increases up to 500 KHz. BI values measured by the BIMS were also in good agreement with those obtained by the CIA. The error rate between BI values measured by the BIMS and CIA was as follows: 1.39% for 10 KHz, 0.72% for 50 KHz, 2.78% for 100 KHz, 7.52% for 150 KHz, 2.88% for 200 KHz, 2.77% for 300 KHz, 4.55% for 400 KHz, and 0.87% for 500 KHz. Curves (b) in Fig. 5(a) show BI for the circuit suggested in Fig. 4(b). BI decreases from 10 to 50 KHz and then is almost constant above 50 KHz up to 500 KHz. The error rate of BI measured using the BIMS and CIA was as follows: 1.24% for 10 KHz, 0.77% for 50 KHz, 0.59% for 100 KHz, 0.23% for 150 KHz, 0.32% for 200 KHz, 1.38% for 300 KHz, 1.54% for 400 KHz, and 1.94% for 500 KHz. Fig. 5(b) illustrates a logarithmic plot of the impedance (Z) as a function of applied frequency (Hz) and energy (eV). BI values measured by the BIMS were in excellent agreement with those measured by the CIA, indicating a good performance of the BIMS for accurately measuring BI. In particular, curves (a) and (b) have different slopes of log Z vs. log f at 4.7 Hz (also 0.20 eV), indicating two different flows of a current in Fig 4(b).



(a)



(b)

Fig. 5. Results of BI measured by BIMS and CIA: (a) BI vs. Frequency for RC circuits, (b) Log plot of Impedance vs. Frequency and Energy for RC circuits

In order to evaluate the clinical significance of the BIMS, after selecting the experimental subjects, BI was measured at the left and right forearm and at the popliteal regions using the BIMS. The experimental subjects were ten male adults with a mean age of 27.5 (±2.5 years), average height of 173 cm (±3.2 cm), and average mass of 75 kg (±4.1 kg). Thirty minutes before the experiment, drinking and smoking was prohibited, and subjects were recommended to be comfortable in the spine posture. Each measurement was conducted again after taking a 10 minute break. Each experiment was conducted five times for the 10 subjects using the BIMS. There was a break period of 10 minutes between each experiment.

Fig. 6(a) shows BI measured with the BIMS according to the frequency when IP electrode with distance of 7 cm was attached to the left and right forearm and the popliteal region. BI values measured at the left and right forearms were 1.54 kΩ and 1.56 kΩ at 10 KHz, respectively. BI rapidly decreased from 10 to 50 kHz and then gradually decreased when HF current above 50 KHz was applied to the tissue in the human body. As shown in the curves (below) in Fig. 6(a), BI at the left forearm is slightly smaller than BI at the right forearm. These occur because of the amount of muscle in the forearms, the capacitance and resistance of the cell, the permeability and conductivity of the cell membrane, the morphological structure of cell, and differences in tissue distribution.

On the other hand, BI values measured at left and right popliteal region were 1.62 kΩ and 1.67 kΩ at 10 KHz, respectively. BI gradually decreased when HF current above 50 KHz was applied to the tissue in the human body. This is due to the fact that BI is lowered since HF AC current flows in both ECF and ICF [17], [18]. BI at the left popliteal region is slightly lower than BI at the right popliteal region. When comparing BI measured at the forearms and the popliteal region, BI values at the popliteal regions were larger than BI values at the forearms. This is due to the fact that muscles at popliteal region consist of structural myofibrils and myofilaments whereas those at forearms are oriented parallel to the current flow. These findings are in good agreement with reports by other investigators, proposing that the orientation of various tissues in the body can affect the impedance reading [24]. Fig. 6(b) illustrates the logarithmic plot of the impedance (Z) as a function of applied frequency (Hz) and energy (eV). Curves have different slopes of log Z

vs. log f at 4.7 Hz (also 0.20 eV), indicating that there are two mechanisms for the current flow in the cell before and after 4.7 Hz (also 0.20 eV). Furthermore, curves have another different slops of log Z vs. log f at 5.48 Hz (around 300 kHz and also 1.24 eV), indicating another mechanism for the current flow in the cell (also impedance shift) of the forearms and popliteal regions.

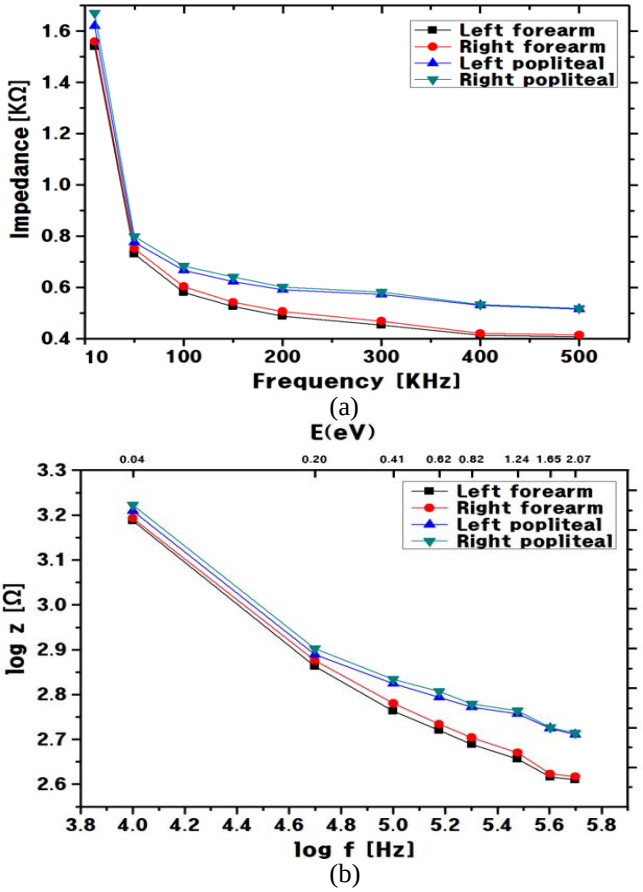


Fig. 6. BI as a function using the BIMS frequency: (a) BI vs. frequency and (b) Log plot of BI vs. frequency.

BI values measured by the BIMS with a constant AC current of 500 μA and an IP electrode with a distance of 7 cm at 50 KHz in this study are as follows: 730.7 Ω at the left forearm, 751.2 Ω at the right forearm, 775.4 Ω at the left popliteal region, and 796.3 Ω at the right popliteal region. These BI values are significantly different from those reported in Scheltinga's study [10]: 221±10 Ω at the arm, 240±7 Ω at the leg. In fact, they measured the resistance of the whole body and its segments with two electrodes which apply AC current of 800 μA at 50 kHz. The differences in BI values occur because of the difference in applied currents - 500 μA and 800 μA, since BI is inversely proportional to the current according to Ohm's law (R=V/I). In addition, BI also varies based on the attaching position of IP electrode, the distribution of muscle and tissue, and the morphological structure and orientation of muscle tissue.

Figure 7(a) shows BI at a right forearm according to frequency when the distance between IP electrodes was changed from 3 to 7 cm in 2 cm intervals. BI values were about 1542±18.3 Ω at 10 KHz. However, BI values showed a significant difference according to the distance between IP electrodes. This corresponds well to the fact that the resistance (or impedance) is proportional to the resistivity and the length, and inversely proportional to the cross section of the biomaterial. This is shown in the following equation of Ohm's equation:

$$R = \rho \frac{L}{A} \quad (5)$$

where, ρ means the resistivity, L the length, and A the cross-sectional area.

Figure 7(b) shows a logarithmic plot of the impedance (Z) as a function of applied frequency (Hz) and energy (eV) when the distance between IP electrodes was changed from 3 to 7 cm in 2 cm intervals.

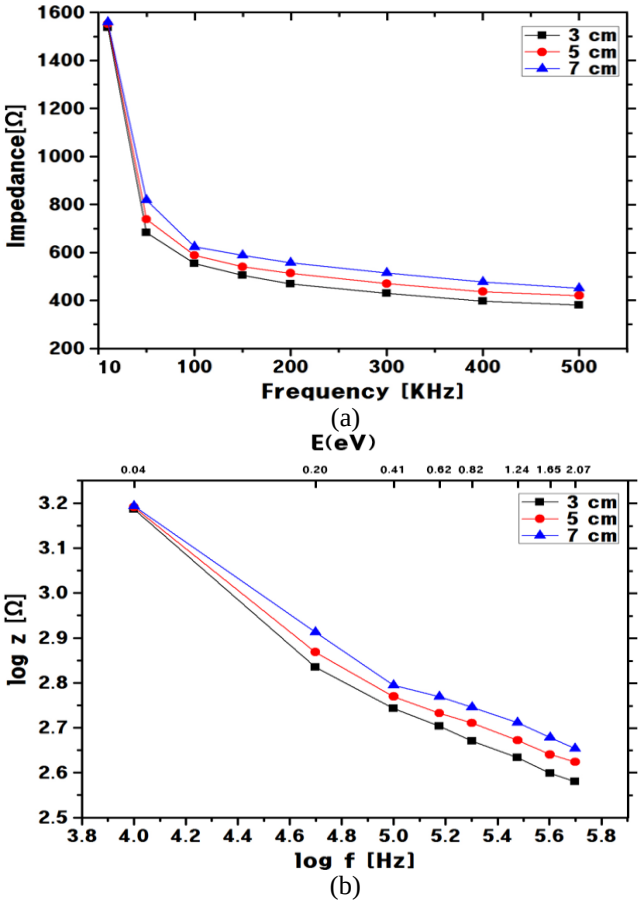


Fig. 7. BI measured at a right forearm as a function of frequency for the distance between IP electrodes: (a) BI vs. frequency and (b) Log plot of BI vs. frequency.

Fig. 8(a) shows BI of ECF and ICF at the right forearm according to the frequency when the distance between IP electrodes was changed from 3 to 7 cm in 2 cm intervals. BI of ECF was measured at eight frequencies ranging from 10 to 500 KHz using the BIMS. BI values of ICF at each frequency ranging from 50 to 500 KHz were calculated by subtracting BI values of ECF measured at 500 KHz from BI values measured at each frequency ranging from 50 to 500 KHz [17, 18]. Both ECF and ICF sharply decreased from 10 to 50 KHz and then gradually decreased up to 500 KHz. In particular, BI of ICF at 10 KHz approached infinity - beyond the range of our measurements. Both ECF and ICF are highly conductive, because they contain salt ions. The membrane of cells is an insulator, which prevents current at low frequencies from

entering the cells. At low frequencies, almost all the current flows through ECF only, so the total BI is largely resistive and equivalent to that of ECF. As this is usually about 20% or less of the total tissue, the resulting BI is relatively high. At the higher frequencies, the current can cross the capacitor of the cell membrane and so enters ICF as well. Since the current has access to the conductive ions in both ECF and ICF, BI sharply decreases [25]. Fig. 8(b) illustrates a logarithmic plot of the impedance (Z) as a function of applied frequency (Hz) and energy (eV). The current with 10 KHz has the energy of 0.04 eV but the cell membrane has the potential barrier (i.e., ionic selective channels) around 0.2 eV as shown in Fig 8(b). In particular, BI of ICF sharply decreases since the capacitance of the cell membrane rapidly decreases above 300 kHz and then approaches zero at 500 KHz [21], [26].

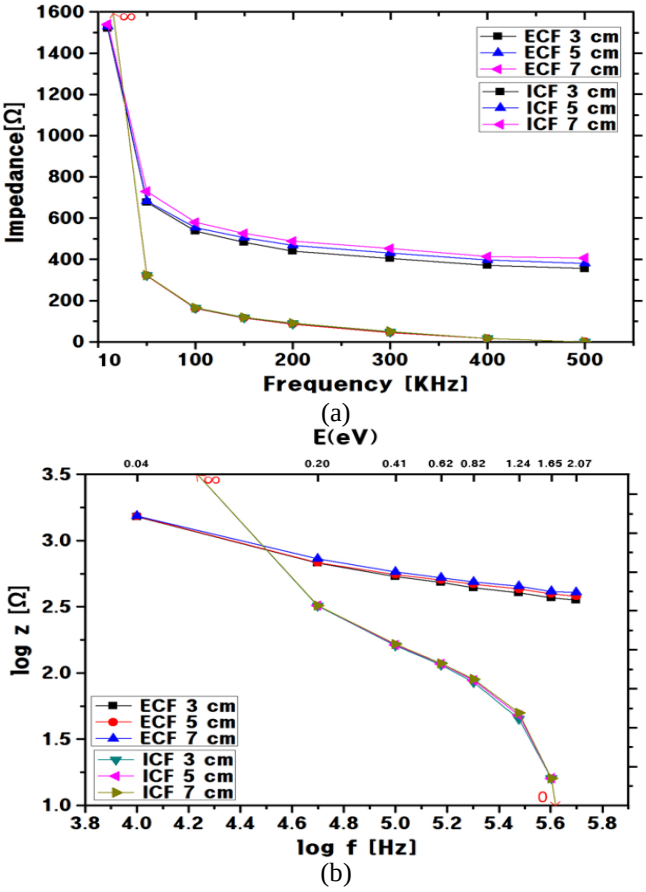


Fig. 8. BI of measured ECF and calculated ICF as a function of frequency for the distances between IP electrodes: (a) BI of ECF and ICF vs. frequency, (b) Log plot of BI of ECF and ICF.

IV. Conclusion

The BIMS for measuring BI at body segments was implemented in this study. BI was measured at the left and right forearm and the popliteal regions using the multi-frequency BIMS with IP electrode. The experimental results for evaluating the performance and verifying the clinical efficiency of the BIMS are as follows.

1. BI was measured for two types of RC circuits consisting of R and C. BI measured by the BIMS was in good agreement with that measured by the CIA. Thus, the BIMS implemented in this study proved to be capable of accurately measuring BI at the segments of the human body.
2. After attaching IP electrode with the separation of 7 cm to the left and right forearm and the popliteal regions, BI was measured at eight frequency ranging from 10 to 500 KHz. Experimental results indicated that BI was observed to be high at 10 kHz and then gradually decreased from 50 to 500 KHz. BI measured using the BIMS and CIA exhibited the error rates of 1.2 % at LF and 1.74% at HF, respectively.
3. A logarithmic plot of impedance (Z) as a function of applied frequency (Hz) and energy (eV) illustrated that BI had different slops of log Z vs. log f at 4.7 Hz (also 0.20 eV) and 5.48 Hz (also 1.24 eV), respectively, indicating that there were two mechanisms for the current flow in the cell before and after 4.7 Hz (also 0.2 0 eV) and 5.48 Hz (also 1.24 eV).
4. BI was measured at a right forearm when the distance between IP electrodes was changed from 3 to 7 cm in 2cm interval. BI of both ICF and BCF rapidly decreased from 10 to 50 KHz and then gradually decreased up to 500 KHz. BI values of ECF were measured differently according to the distance between IP electrodes, but BI values of ICF were almost the same regardless of the distance between IP electrodes.
5. In particular, a constant AC current with 10 KHz does not flow through the cell membrane. This is due to the fact that the current of 10 KHz has the energy of 0.04 eV but the cell membrane has the potential barrier (i.e., ionic selective channels) around 0.2 eV. A logarithmic plot of BI vs. frequency showed that BI of ICF was largely decreased because the capacitance of the cell membrane rapidly decreased above 300 kHz and then was approaching zero at 500 KHz.

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