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복합형 전극의 특성을 이용한 피부의 전기저항 측정에 관한 연구

우 응 제

=Abstract=

Skin Impedance Measurements Using the Characteristics of Compound Electrode

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We studied the characteristics of the compound electrode and found that the compound electrode provides the four-electrode method in a compact form. We developed a new method of measuring the skin impedance using simple electrodes at low frequencies. At high frequencies where the effect of internal tissue impedance is not negligible, we used the compensation method using compound electrodes since they measure the voltage right under the skin. At 50 kHz, we measured the real part of the skin impedance of less than 80Ω on the thorax. We propose a simple instrument which can measure accurate skin impedance at various frequencies.

1. INTRODUCTION

Electrical characteristics of the skin has been receiving increasing attention in electropathology, measurement of biopotential, external electrical stimulation, measurement of bio-impedance, and other areas where surface electrodes are used. Especially, in electrical impedance tomography (EIT) where we apply electrodes to the skin to measure potential on the body surface, the high unknown electrode-skin contact impedance causes a problem since a large voltage drop across it may mask a small voltage drop due to the internal body tissues. Therefore, knowledge of the skin impedance is very helpful in the reconstruction of static resistivity images [1][4].

Since the skin impedance dominates the metal-to-electrolyte impedance at frequencies from 1 H to 1

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MHz, in this paper. we will use the term skin impedance to mean electrode-skin contact impedance. Several researchers have measured the skin impedance at various locations on the human body at different frequencies [2][5][6-7]. Hua *et at.* [1] developed a finite element model of the electrode-skin or electrode-electrolyte interface for use in EIT.

In this paper, we developed a simple and fast real-time method of measuring the skin impedance under each of the 32 electrodes. We also prosent a compensation method which produces more accurate skin impedance values at high frequencies, by removing the effect of the internal body impedance from the measured skin impedance using compound electrodes. The measurements of skin impedance using the technique descrived in this paper will be useful in EIT [1][4], in the measurement of skin mosisturisation [5], and also in the study fo the electrical characteristics of the skin [6-7].

2. TWO－US. FOUR－ELECTRODE METHOD

There are two different methods (two-and four-electrode methods) for body impedance measurement [3]. In most cases except for the measurement of the skin impedance, the four-electrode method has been used since it makes it possible to measure only the internal body impedance. Fig. 1 shows the electrode configurations for both methods. In the four-electrode method where we use two sets current flows through the voltage-measuring electrodes due to the very high input impedance of the voltmeter. Therefore, the voltage measured by the four-electrode method(V_{cd})is the voltage across the internal body impedance(Z_{cd}). In the two-electrode method where we use the same electrodes for both current injection and voltage measurement, the measured voltage(Vab) includes the skin impedances(Z_{ac} + Z_{db}) as well as the internal body impedance (Z_{cd}).

The important observation from Fig. 1 is that V_{cd}

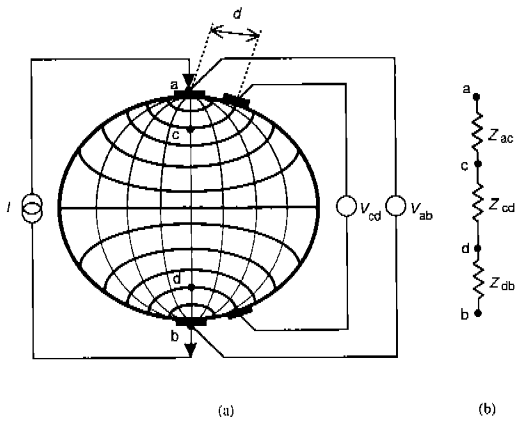

Fig. 1 Two-vs. four-electrode method (a) Assuming that the medium is homogeneous, thin lines are current stream lines and thick lines are equipotential lines (b) Simplified lumped parameter model of (a)

depends on the distance d since V_{cd} is a voltage different between two equipotential lines determined by the internal resistivity distribution and d. Therefore, the locations of the voltage-measuring electrodes are very important in measuring the impedance changes of internal organs.

3. COMPOUND ELECTRODE

The compound electrode shown in Fig. 2(a) provides the four-electrode measurement method in a compact form. We placed a compound electrode and a simple reference electrode on the skin and measured the change of voltages within, on, and outside the current-injecting part of a compound electrode. As shown in Fig. 3, there is only a small voltage change due to the edge effect within the current-injecting part of a compound electrode. On the current-injecting part of a compound electrode, the measured voltage increased abruptly since we achieve a two-electrode method. Outside the current-injecting part of a compound electrode, the voltage decreases since d in Fig. 1 increases. Therefore, as

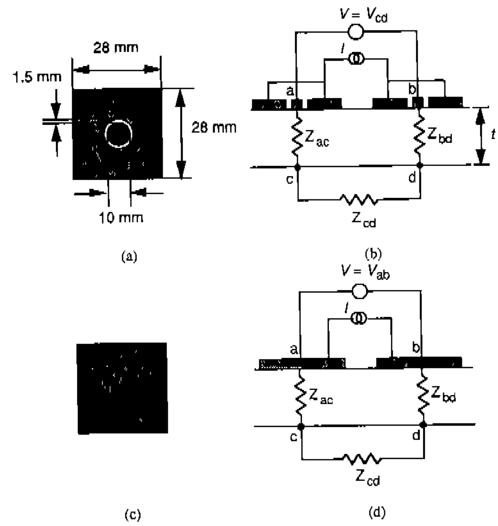

Fig. 2 (a) Compound vs. (c) simple electrode

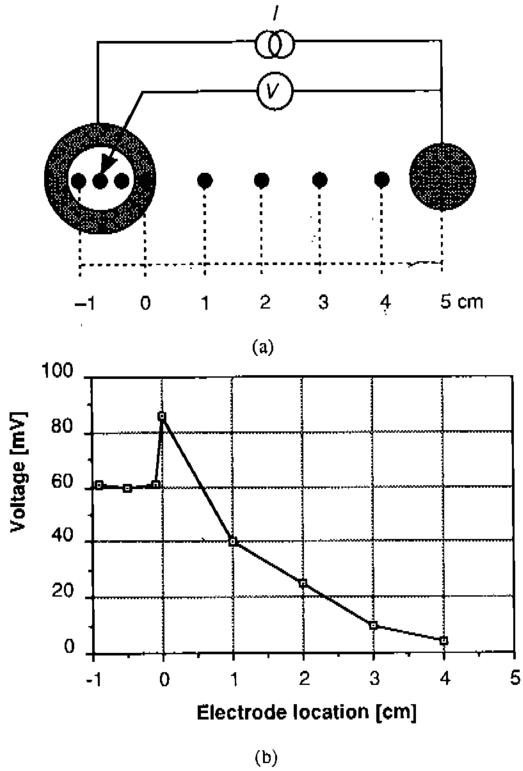

Fig. 3 (a) Electrode configuration and (b) measured change of voltage within, on, and ouside the current-injecting part of a compound electrode

shown in Fig. 2(b), the compound electrode measures the voltage between two points under the barrier layer of the skin by using a voltmeter with a high input impedance. Compared to compound electrodes, simple electrodes measure skin impedance as well as internal tissue impedance as shown in Fig. 2 (d).

When we used two compound electrodes, we could measure an impedance value of $237\angle -15^{\circ}\,\Omega$ between two points on the abdomen. When we used two simple elecrodes, the impedance value between the same two points was $366\angle 37^{\circ}\,\Omega$. Then, after we applied and removed Scotch tape on those two locations 16 times to remove the outermost layer of the skin, the impedance value using the two-electrode method was reduced to $267\angle -26^{\circ}\,\Omega$.

By comparing the above three impedance values, we can deduce the following facts. First, when we used the compound electrodes, the voltage measurement points (c and d in Fig. 2(b) are below the barrier layer of the skin which we removed by the repeated application and removal of Scotch tape. Second, the changes in phase indicate that the outermost layer of the skin has a large capacitance and internal body impedance is not capacitive. Third, the impedance measured by the compound electrodes includes the impedance of the body tissues excluding only the skin whereas the internal body impedance measured by the traditional four-electrode method(usually less that 50Ω) excludes some part of internal body tissues as well as the skin depending on the eletrode configuration.

Yamamoto and Yamamoto [6] removed the outer layers of the skin by applying and removing Scotch tape repeatedly and plotted the impedance of the skin as a function of the number of strippings. Their results showed that the resistivity and dielectric constant of the skin drop rapidly at low frequency as a function of stripping. However, at high frequency, both the resistivity and dielectric constant remain at the initial small values. This means that at high frequency, the impedance of the outermost layer of the skin is small and almost the same as that of the inner layers.

Though the four-electrode method including the compound electrode is used in almost al impedance measurement, we need to use the two-electrode method to measure the skin impedance itself. In the next section, we describe a simple and fast method and a compensation method for measuring the skin impedance.

4. MEASUREMENT OF SKIN IMPEDANCE

For a human subject, let's first assume that the internal body impedance is negligible compared to the skin impedance. This assumption is valid at low frequencies as demonstrated by the experimental results by Yamamoto and Yamamoto [6]. We place E simple electrodes around a subject and model the skin impedance under each electrode as a single lumped impedance Z_i, then the equivalent circuit becomes a star network as shown in Fig. 4.

We apply a constant source to each adjacent pair of electrodes and measure a voltage across the two electrodes as shown in Fig. 5(a). Then,

$$Z_1+Z_2=\frac{V_{1-2}}{I}$$

$$Z_2+Z_3=\frac{V_{2-3}}{I}$$

$$Z_E+Z_1=\frac{V_{E-1}}{I}$$

Since we cannot determine each skin impedance $Z_i(i=1, \cdots, E)$ from the above equations, we need to make another set of measurements. Now, we inject current I to a pair of electrodes separated by an additional one in the middle and measure voltage as shown in Fig. 5(b). Then,

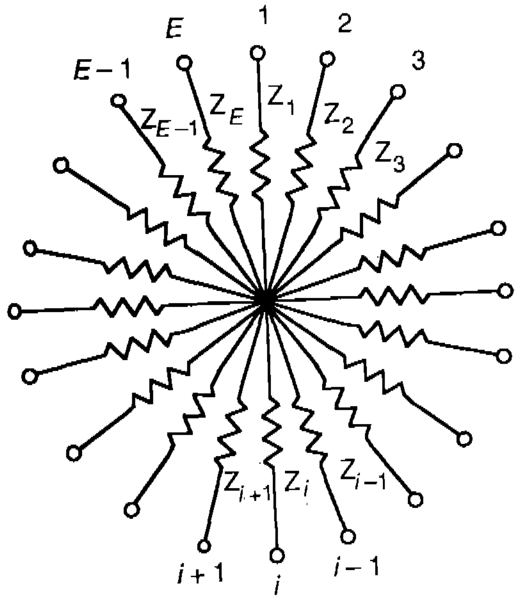

Fig. 4 Star network

$$Z_1+Z_3=\frac{V_{1-3}}{I}$$

$$Z_2+Z_4=\frac{V_{2-3}}{I}$$

$$Z_E+Z_2=\frac{V_{E-2}}{I}$$

Adding the first and the last equation in Eq. (1),

$$2Z_1+Z_2+Z_E=\frac{V_{1-2}}{I}+\frac{V_{E-1}}{I}$$

Then, from the last equation in Eq. (2),

$$Z_1=\frac{V_{1-2}+V_{E-1}-V_{E-2}}{2I}$$

Therefore, in general,

$$Z_i=\frac{V_{i-[i+1]}+V_{[i-1]-i}-V_{[i-1]-[i+1]}}{2I}$$

where we divide the contents within [] by E and replace [] by the remainder.

If the assumption about the negligible internal body impedance compared to that of the skin is true, then, after we compute Z_1, we can simply calculate all other skin impedances by substitutions in Eq. (1). However, this method produces a larger

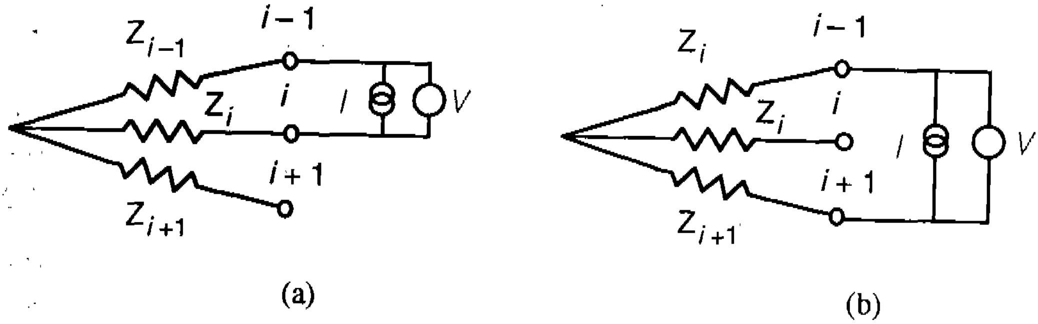

Fig. 5 Measuring skin impedance (a) between adjacent electrodes, and (b) skipping one electrode

error in the calculated skin impedances since the error is accumulated. For most practical purposes, therefore, we need to make two sets of measurements (Eq. (1) and Eq. (2)). Then, by using Eq. (5), we can compute all skin impedances. Figure 6 shows the skin impedances at 50 kHz under 16 simple electrodes computed by Eq. (5).

The fact that the method by substitution produces large errors indicates that the internal impedances are not really negligible. Therefore, when we need to measure the skin impedances very accurately, we need to consider the effect of the interanl impedance especially at high frequencies.

5. COMPENSATION USING THE COMPOUND ELECTRODE

By using the compound electrode shown in Fig. 2 (a), we can effectively measure only the internal tissue impedance. Then, from Fig. 2(d), when we use simple electrodes,

$$V_{i-[i+1]} = (Z_i + Z_{cd} + Z_{i+1})I$$

where Z_{cd} is the internal body impedance. And, when we use the compound electrodes, no current flows through Z_i and Z_{i+1}. Therefore,

$V_{i-[i+1]} = V_{a-b} = Z_{cd}I$.

Then,

$$Z_i + Z_{i+1} = \frac{V_{i-[i+1]} - \tilde{V}_{i-[i+1]}}{I}$$

Compared to Eq.(1), we can see that the only change is the compensation term $V_{i-[i+1]}$ in each computation of the sum of the skin impedances. In general, each skin impedance Z_i can be computed with compensation as follows :

$$Z_i = \frac{V_{i-[i+1]} - \tilde{V}_{i-[i+1]} + V_{[i-1]-i} - \tilde{V}_{[i-1]n} - V_{[i-1]-[i+1]}\tilde{V}_{[i-1]-[i+1]}}{2I}$$

where $i = 1, \cdots, E$.

By using the compensation method where we use both two-and four-electrode measurement mothods to measure one skin impedance, we can minimize the effect of the internal body impedance. Fig. 6 shows the measured skin impedances of the thorax under 16 electrodes with and without compensation. We can see that the skin impedance varies depending on the location on the thorax. At 50kHz,

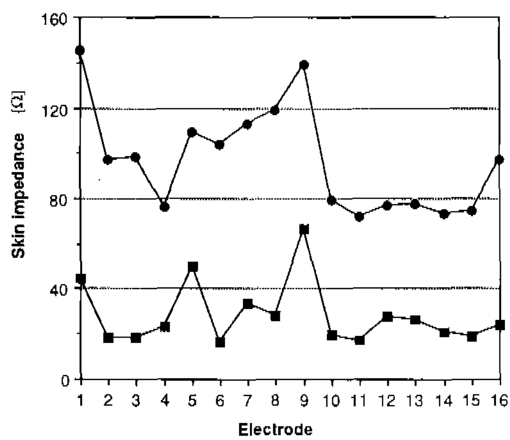

Fig. 6 Measured skin impedance on the thorax under 16 elecrodes with and without compensation

the internal body impedance measured at the thorax was about 70Ω and the skin impedance varied from about 20 to 70Ω. Figure 7 shows the measured electrode-electrolyte contact impedances of a two-dimensional physical phantom using 32 stainless steel electrodes with and without compensation. We can see that the contact impedance of the electrode is very small(about 2 or 3Ω) since there is no barrier like the skin in the phantom.

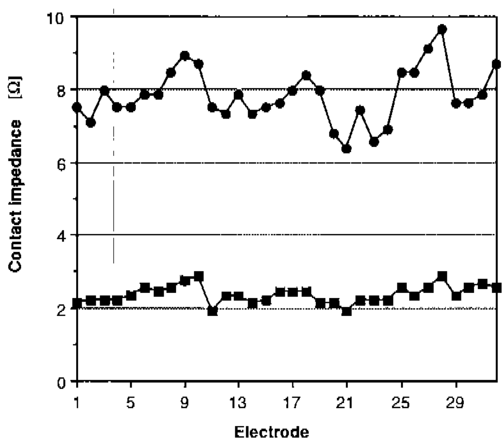

Fig. 7 Measured contact impedance of the physical phantom (30cm diameter) filled with 100Ω-cm saline solution using 32 electrodes with and without compensation

6. CONCLUSION

We found that at 50kHz, the impedance of the skin is less than 50% of the impedance of the internal tissues. Therefore, the skin impedance at 50kHz is considerably smaller than that at lower frequency. However, the compound electrode is still useful in impedance imaging in eliminating the effect of the skin since the boundary voltage is much more sensitive to the perihery than the center.

Our results also indicate that the impedance measured by the four-electrode method is very dependent upon the electrode configuration. We could measure 20 to 300Ω of internal body impedance depending on the electrode configuration.

The simple method of measuring the skin impedance is reasonably accurate. This method requries three voltage measurements in the neighborhood of the point of interest using the two-electrode measurement method by simple electrodes. We can increase the accuracy of the measured skin impedance by the compensation method. In the compensation method, we need three voltage measurements using simple electrodes and another three voltage measurements using compound electrodes by the four-electrode method. The compensation method using the six-voltage data produces accurate skin impedance by removing the effect of the internal body impedance.

Based on the skin impedance measurement method described in this paper, we can develop a simple instrument which measures the skin impedance accurately at various frequencies. This instrument will include a current source with variable frequency, a voltmeter, and a switching circuit. We will also need three compound electrodes which can be configured as simple electrodes by the switching circuit.

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