복합형 전극을 이용한 피부의 전기저항 측정

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SKIN IMPEDANCE MEASUREMENTS USING COMPOUND ELECTRODES

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ABSTRACT

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 80 Ω on the thorax.

INTRODUCTION

When we apply electrodes to the skin in electrical impedance tomography (EIT), the 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. Since the skin impedance dominates the metal-to-electrolyte impedance at frequencies from 1 Hz to 1 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 [1, 3, 4, 5].

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 present a compensation method which produces more accurate skin impedance values at high frequency by removing the effect of the internal body impedance from the measured skin impedance using compound electrodes. The measurement of skin impedance will be useful especially in an EIT system using simple electrodes.

TWO- vs. FOUR-ELECTRODE METHOD

There are two different methods (two- and four-electrode methods) for body impedance measurement [2]. 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. Figure 1 shows the electrode configurations for both methods. In the four-electrode method where we use two sets of separate electrodes for current injection and voltage measurement, ideally no 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 (V_{ab}) 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} depends on the distance d since V_{cd} is a voltage difference 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.

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 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 $237\angle-15°$ Ω between two points on the abdomen. When we used two simple electrodes, the impedance value between the same two points was $366\angle-37°$ Ω. 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 $267\angle-26°$ Ω.

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 than 50 Ω) excludes some part of internal body tissues as well as the skin depending on the electrode configuration.

Yamamoto and Yamamoto [4] 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 all 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.

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 [4]. 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 current source to each adjacent pair of electrodes and measure a voltage across the two electrodes as shown in Fig. 5(a). 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,

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

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

When we need to measure the skin impedances very accurately, we need to consider the effect of the internal impedance especially at high frequencies. 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,

$$V_{i\text{-}[i+1]} = (Z_i + Z_{cd} + Z_{i+1})\, I \tag{2}$$

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,

$$\tilde{V}_{i\text{-}[i+1]} = V_{a\text{-}b} = Z_{cd}\, I. \tag{3}$$

Then,

$$Z_i + Z_{i+1} = \frac{V_{i\text{-}[i+1]} - \tilde{V}_{i\text{-}[i+1]}}{I}. \tag{4}$$

In general, each skin impedance Z_i can be computed with compensation as follows:

$$Z_i = \frac{V_{i\text{-}[i+1]} - \tilde{V}_{i\text{-}[i+1]} + V_{[i-1]\text{-}i} - \tilde{V}_{[i-1]\text{-}i} - V_{[i-1]\text{-}[i+1]} + \tilde{V}_{[i-1]\text{-}[i+1]}}{2I} \tag{5}$$

where $i = 1, \ldots, E$. Compared to Eq. (1), we can see that the only change is the compensation term $\tilde{V}_{i\text{-}[i+1]}$ in each computation of the sum of the skin impedances.

By using the compensation method where we use both two- and four-electrode measurement methods to measure one skin impedance, we can minimize the effect of the internal body impedance. Figure 6 shows the measured skin impedances of the thorax under 16 electrodes with and without compensation at 50 kHz.

CONCLUSIONS

We found that at 50 kHz, the impedance of the skin is less than 50% of the impedance of the internal tissues. Therefore, the skin impedance at 50 kHz 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 periphery 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 300 Ω of internal body impedance depending on the electrode configuration.

The simple method of measuring the skin impedance is reasonably accurate. This method requires 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.

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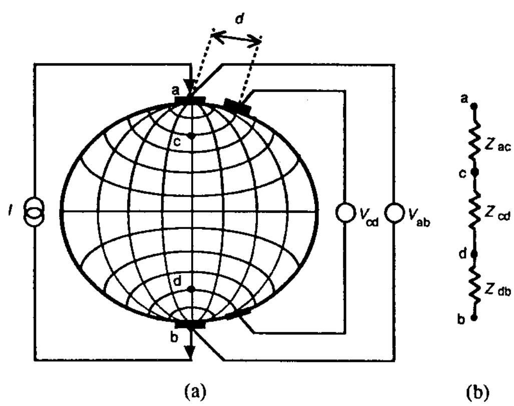

Figure 1 Two- vs. four-electrode method. (a) Assuming that the medium is homogeneous, thin lines are current stream lines and thick lines are equipotential lines. (b) Simplified lumped parameter model of (a).

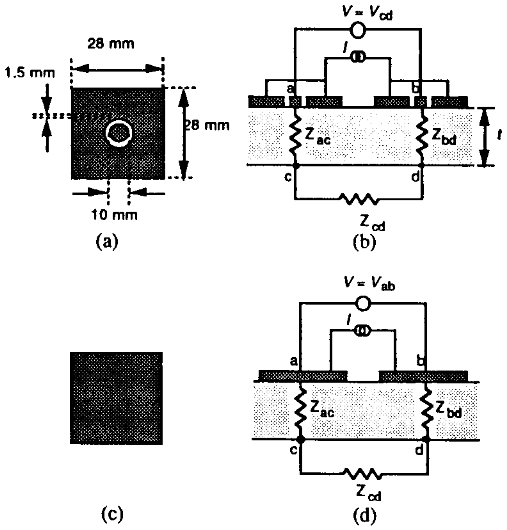

Figure 2 (a) Compound vs. (c) simple electrode.

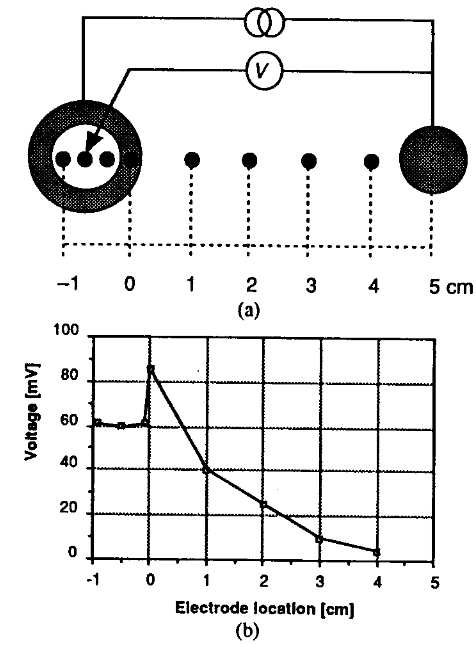

Figure 3 (a) Electrode configuration and (b) measured change of voltage within, on, and outside the current-injecting part of a compound electrode.

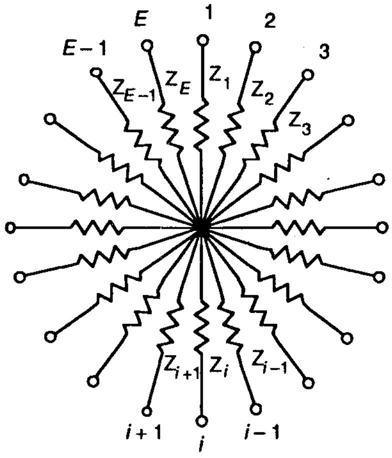

Figure 4 Star network.

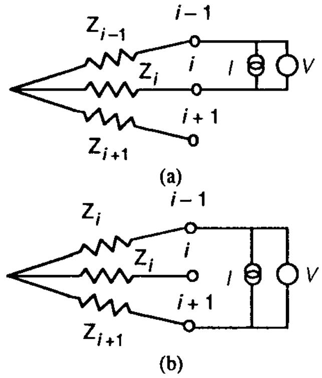

Figure 5 Measuring skin impedance (a) between adjacent electrodes, and (b) skipping one electrode.

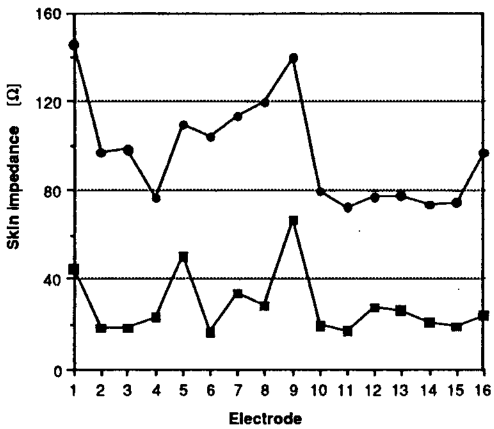

Figure 6 Measured skin impedance on the thorax under 16 electrodes with ■ and without ● compensation.