Evaluation of Lower-Leg Swelling using Electromyograms Obtained with Voltage-Dividing Electrodes

Akito Murai¹, Yusuke Sakaue¹ and Masaaki Makikawa²*

¹Graduate School of Science and Engineering, Ritsumeikan University, Japan
²College of Science and Engineering, Ritsumeikan University, Japan

Abstract

Lower leg swelling is caused by an increase in extracellular fluid in the lower leg. Lower leg swelling is uncomfortable for the patient and increases the risk of blood flow abnormalities. Compression stockings, leg exercise, and a specific type of flooring material have been used to attempt to prevent lower leg swelling. To evaluate lower leg swelling, we attempted to estimate the change in internal impedance due to lower leg swelling using electromyograms (EMG) obtained with voltage dividing electrodes. Ten healthy men (23.3±2.1 years old) participated in this study. They were asked to work at a desk for 12 hours. The following measurements were obtained: EMG readings (obtained using voltage dividing electrodes), calf circumference, and lower leg impedance (obtained using an impedance meter). These measurements were obtained before, during and after the desk work. The results showed that the internal impedance decreased as the calf circumference increased. The reduction ratio of the internal impedance, as determined by EMG performed with voltage dividing electrodes, was significantly greater than the internal impedance measured using an impedance meter (P<0.05). Our new measurement method was thus proven to be effective in evaluation of lower leg swelling.

ABBREVIATIONS

EMG: Electromyogram; BIA: Bioelectrical Impedance Analysis

INTRODUCTION

In this paper, a new method for evaluation of lower leg swelling using electromyograms (EMG) obtained with voltage dividing electrodes is introduced [1]. Lower leg swelling occurs as a result of an increase in extracellular fluid in the lower leg. In daily life, extracellular fluid circulates around the body by blood and lymph flow, and both types of fluid circulation are driven by muscle and heart pumping activities. A reduction in these pumping activities causes poor circulation of extracellular fluid and an increase in extracellular fluid in the lower leg. Lower leg swelling is painful and uncomfortable and increases the risk of blood flow abnormalities. Compression stockings, leg exercises, and specific types of flooring materials have been used to attempt to prevent lower leg swelling [2-4].

Typically, lower-leg swelling is evaluated by measuring the calf circumference using a tape measure [5]. Lower leg swelling is easily measured by this method, but large measurement errors may result. Bioelectrical impedance analysis (BIA) is also used to evaluate lower leg swelling [6]. In BIA, the reduction in bioelectrical impedance associated with increased extracellular fluid is measured. To calculate the bioelectrical impedance, an alternating current (AC) of more than 100 kHz is applied to the human body [7]. There is a low-frequency AC is not used in BIA is that low-frequency current poses risks of electrical shock and pacemaker malfunction.

We have developed a new signal source estimation method that uses voltage divider technology [8]. Using this method, biological signals are measured with and without additional resistance between the signal electrode and the ground electrode, and the signal source potential is attenuated by a voltage divider consisting of internal impedance and additional resistance. The signal source position is estimated from the attenuation level of the signalsource potential. In our study, we attempted to estimate the internal impedance using surface EMGs of lower extremities measured with and without use of a voltage divider. The theory and details of our measurement method are described in the next section.

Our method employs surface EMG measurement, which poses no risk of electrical shock or pacemaker malfunction.
unlike BIA. The frequency band of the surface EMG signal passing through the human body is lower than the frequency band of the AC used in BIA. Low frequency AC passes only through only the extracellular fluid [9]. We therefore expected our method to be able to evaluate the change in internal impedance due to an increase in extracellular fluid with high sensitivity.

The purpose of this study was to evaluate lower leg swelling using EMGs measured using voltage dividing electrodes. The amplitude of an EMG measured without a voltage divider was compared to that measured with a voltage divider to calculate the bioelectrical impedance of the lower leg. Experiments were carried out to measure changes in the bioelectrical impedance of the lower leg before and after lower leg swelling.

MATERIALS AND METHODS

Theory

A model of the lower leg is shown in Figure 1A. To measure biosignals using surface electrodes, the human body can be replaced by an electrical circuit comprising a signal source, and the conductivity within the human body can be assumed to be uniform for simplicity [10]. Using the venin’s theorem, the human body can be replaced by a signal source and synthetic impedance between the signal source and electrodes [11,12]. The model for our measurement system is shown in Figure 1B, the measurement circuit is shown in Figure 1C. The muscle is replaced by a signal source with potential $V_S$. In this study, skin surface EMGs were measured using the bipolar-lead method. Soft tissues inside the body are replaced by three synthetic impedances, $Z_b1$, $Z_b2$, and $Z_g$, one to each electrode. The additional resistance $R_E$ is set to be positive or negative using a mechanical switch. The voltage divider consists of the additional resistance $R_E$ and the two internal impedances $Z_b1$ and $Z_b2$, and the signal source potential is attenuated at each electrode.

Because the input resistance $R_i$ of the amplifier is very large (10TΩ), the signal source potential is not attenuated when the additional resistance is switched off. Eq.(1) expresses the output potential $V_{out}'$ when the additional resistance is switched off. Eq.(2) expresses the output potential $V_{out}''$ when the additional resistance is switched on, and the signal source potential is attenuated. The attenuation level of the signal source depends on the additional resistance and internal impedance, i.e., the soft body tissue. Eq.(3) is used to calculate the total value of the two internal impedances obtained from eqs.(1) and (2). In this study, the total value of the two the internal impedances, $Z_b$ is used to evaluate lower-leg swelling.

$$V_{out} \approx V_S.$$  

$$V_{out}' = \frac{R_E}{Z_{b1} + Z_{b2} + R_E} V_S.$$  

$$Z_{b1} + Z_{b2} = Z_b = \frac{V_{out} - V_{out}'}{R_E}.$$  

Subjects

Ten healthy adult men (23.3±2.1 years old) with no history of lower extremity problems participated in this study. The subjects were asked to work at a desk for 12 hours to induce extracellular retention in the lower leg, and the $Z_b$ of each subject was measured before, during, and after the desk work, using the procedure described in the next section. During the 12 hours of desk work, the subjects were not allowed to move from the desk except when necessary to eat lunch and use the washroom. The subjects were not allowed to wear such things as stockings, long socks, or tights that are considered to assist in blood flow and reduce lower leg swelling. They were asked to sleep for at least

![Figure 1](image_url)
seven hours on the day before the experiment and not to drink alcohol. The experiments were conducted in accordance with the ethical principles of the Helsinki Declaration after obtaining informed consent from the subjects.

Measurement

EMG measurements performed using voltage-dividing electrodes were carried out before, during, and after the desk work. The target muscle of the surface EMG was the lateral gastrocnemius of the right foot. Figure 2 shows the positioning of the signal electrodes \( e_1 \) and \( e_2 \) and the ground electrode \( e_3 \). A pair of signal electrodes was set on the muscle belly of the lateral gastrocnemius. The distance between the two signal electrodes was 25 mm. The ground electrode was set on the right tibia at the same height as the signal electrodes. Disposable electrodes (SP-00-S, Mets Co., Ltd.) were used in the experiments. Before the electrodes were attached, sebum and dirt were removed using alcohol swabs and wipes.

The surface EMG was measured for 60 s as subjects at with his calf raised and his ankle joint held at a 30 degree angle. Figure 3 shows a photograph of the experiment. The subjects were asked to practice this experimental posture before the measurement for the purpose of EMG amplitude stabilization. Five additional resistances (1, 3, 5, 9, and 15 kΩ) were set between positive and negative inputs using a mechanical switch to confirm that the change in attenuation depended on the additional resistance. The experimenter switched the five additional resistances on and off every 10 s. The total gain of the amplifier with a high pass filter of 10 Hz, shown in Figure 1C, was 84 dB. The sampling frequency was 1,000 Hz.

Before every EMG measurement, the calf circumference was measured using a tape measure and the bioelectrical impedance between electrode \( e_1 \) and \( e_2 \) \( (Z_{\text{Ref}}) \) were measured using impedance meter (35-3250, Hioki Co., Ltd.). The calf circumference was measured while a subject stood and relaxed his lower leg. The measurement point was marked to ensure that the same point on the calf of each subject was measured. \( Z_{\text{Ref}} \) was measured over a period of 10 s using an impedance meter, with each subject assuming the same posture as in the calf circumference measurement. The sampling frequency was 1 Hz, and the voltage applied ranged from 0.01 V to a limit corresponding to a current less than 10 μA at which the subjects did not feel pain or numbness. The AC frequency between \( e_1 \) and \( e_3 \) was 50 kHz, as is typical in BIA to compare the impedance at low frequency with high frequency.

Data analysis

The EMG data for 60 s intervals were divided into six sets of 10 s data. Next, data for between 2 and 8 s were extracted, and artifacts contaminating the measurement data were eliminated using a digital band-pass filter of 15-500 Hz. For each set of data filtered from 15 to 500 Hz, the root mean square (RMS) was calculated. The RMS calculated from the EMG without additional resistance was denoted \( V_{\text{out}} \), and that with additional resistance \( V'_{\text{out}} \). Five \( Z_b \) values were obtained for each subject using eq. (3). In this study, the average of three \( Z_b \) values for each subject, excluding the large stand smallest value, was defined as the \( Z_b \) to take into account EMG amplitude variation. \( Z_b \) values were normalized, and change ratios were calculated by comparison with the values obtained from measurements made before the desk work began.

The average \( Z_{\text{Ref}} \) over the measurement period of 10 s was calculated. Both the calf circumference and bioelectrical impedance values were normalized, and change ratios were calculated by comparison with the values obtained from measurements made before desk work began.

RESULTS AND DISCUSSION

Results

Figure 4 shows an example of an EMG waveform measured before the desk work. The EMG amplitude was attenuated by the additional resistances applied in comparison to the EMG amplitude without additional resistance. The attenuation observed when the lowest additional resistance (1 kΩ) was applied was the largest of the attenuations observed for the five additional resistances. The attenuation decreased with each increase in the additional resistance.

Table 1 shows the all subjects of \( Z_b \), \( Z_{\text{Ref}} \), and the calf circumference. For all of the subjects, the calf circumference was greater during and after the desk work than before the desk work. The calf circumference increased 0.2±0.1 cm on average from before to during the desk work and 0.3±0.2 cm on average from before to after the desk work.
Table 1: All subjects of internal impedance ($Z_b$), the bioelectrical impedance measured using an impedance meter ($Z_{Ref}$), and calf circumference (n=10).

<table>
<thead>
<tr>
<th>subjects</th>
<th>$Z_b$[kΩ]</th>
<th>$Z_{Ref}$[Ω]</th>
<th>Calf circumference [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>During</td>
<td>After</td>
</tr>
<tr>
<td>1</td>
<td>27.8</td>
<td>18.9</td>
<td>17.5</td>
</tr>
<tr>
<td>2</td>
<td>7.8</td>
<td>8.8</td>
<td>8.7</td>
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<tr>
<td>3</td>
<td>12.8</td>
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<td>11.3</td>
</tr>
<tr>
<td>4</td>
<td>12.9</td>
<td>11.7</td>
<td>13.0</td>
</tr>
<tr>
<td>5</td>
<td>6.6</td>
<td>4.6</td>
<td>4.7</td>
</tr>
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</tr>
<tr>
<td>8</td>
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</tr>
<tr>
<td>10</td>
<td>11.3</td>
<td>10.4</td>
<td>9.0</td>
</tr>
<tr>
<td>Average</td>
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<td>9.3</td>
<td>9.1</td>
</tr>
<tr>
<td>S.D.</td>
<td>5.6</td>
<td>4.1</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Abbreviations: SD: Standard Deviation

Figure 4 Example of electromyogram (EMG) waveform (no= no resistance).

Figure 5 Change ratios of the total value of internal impedance ($Z_b$) and the bioelectrical impedance measured using an impedance meter ($Z_{Ref}$).
Figure 5 shows the change ratios of $Z_b$ and $Z_{Ref}$. The $Z_b$ values were lower during and after the desk work than before the desk work for all but one subject. The average $Z_b$ decreased by 3.1±2.6 kΩ (−20.5%) from before to during the desk work and decreased by 3.3±3.2 (−25.1%) from before to after the desk work. For all of the subjects, $Z_{Ref}$ was also lower during and after the desk work than before the desk work. The average $Z_{Ref}$ decreased by 23.6±7.5 Ω (−6.7%) from before to during the desk work and decreased by 16.6±13.2 Ω (−6.4%) from before to after the desk work. The change ratio of $Z_b$ during versus after the desk work was significantly greater than that of $Z_{Ref}$ ($P<0.05$).

Discussion

Long-term standing and sitting induce areduction in muscle pump activity and thus contribute to lower-leg swelling [6]. As shown in Table 1, calf circumference was found to increase with long-term deskwork. In this study, male subjects were asked to work at a desk to measure the change in internal impedance with mild lower-leg swelling. Calf circumference was found to increase by 0.3 cm on average.

The increases observed in calf circumference and volumes were brought about by pooling of extracellular fluid in the lower leg. As shown in Figure 5, $Z_b$ and $Z_{Ref}$ measured using an impedance meter both decreased as the calf circumference increased. This finding suggests that long-term desk work induces pooling of extracellular fluid and decreased bioelectrical impedance in the lower leg. However, there were two subjects whose $Z_b$ did not decrease as a result of a lengthy period of desk work. There as on for this is that the subject had an athletic history: his heavy muscle mass inhibited pooling of extracellular fluid.

The impedance measured by conventional bioelectrical impedance method differs according to the frequency of AC current passing through the human body, and it is said that low frequency current should be used to measure the impedance of extracellular fluid [13]. The body tissue can be replaced by three electrical components that are the resistance of intracellular and extracellular fluid, and the capacitance of cell membrane [9]. The $Z_b$ measured at frequency-band of EMG signal mainly indicates the resistance of extracellular fluid, because low frequency current to intracellular fluid is blocked by the capacitance of cell membrane. At high frequency, the impedance of cell membrane is reduced, and current can pass through both intracellular and extracellular fluid. Therefore, the change ratio of $Z_b$ may be significantly greater than that of $Z_{Ref}$ at the current of 50 kHz, when using a conventional impedance meter. Previous study reported that the lower leg impedance decreased about 7% from morning to evening [14]. These results suggest that our measurement system using EMG signals can be used to measure changes in lower-leg impedance with higher sensitivity than a measurement system that uses high-frequency alternating current.

CONCLUSION

In this study, we measured the internal lower-leg impedance between a signal source and signal electrodes using EMG performed with voltage-dividing electrodes. Subjects were asked to work at a desk for a long period of time to induce changes in the internal impedance of the lower leg. The internal impedance was found to decrease with increasing calf circumference, and our results are coincident with previous studies [1,5,6,13,14]. Low frequency AC current should be used to evaluate the lower leg swelling [14]. However, the low frequency AC current has risk of electrical shock e.g. pacemaker malfunction in BIA. In addition, EMG signal may be contaminated as noise in previous bioelectrical impedance methods. Therefore, this study indicates that our measurement system can be used to measure the change in internal impedance of the lower leg with high sensitivity and that EMG measurements performed with voltage-dividing electrodes can be used to evaluate lower-leg swelling and methods to reduce and prevent it.

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REFERENCES
