Changes in Intramuscular Blood Volume Induced by Continuous Shortwave Diathermy

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Abstract. The purpose of this study was to determine the relationship between the changes in intramuscular blood volume (IMBV) under continuous shortwave diathermy (CSWD) and compare them with the electric hot pack (EHP). The subjects consisted of 41 healthy adults, who received one of three interventions: CSWD (n=17), EHP (n=12), or no intervention (Controls: n=12). Analyses were done of the values obtained five minutes preceding the intervention (T1), during the intervention (T2), and after the intervention (T3). CSWD was applied with an output of 80 W. Both CSWD and EHP were applied for 10 min. Changes in IMBV of the right medial gastrocnemius muscle were evaluated using near-infrared spectroscopy (NIRS). Oxy-hemoglobin (oxy-Hb), deoxy-hemoglobin (deoxy-Hb), and total-hemoglobin (total-Hb) were measured using NIRS. At T2 in the CSWD trial, the integration values of oxy-Hb and total-Hb were significantly increased compared with those of the controls (p<0.01), and they were significantly increased compared with those of both the controls and the EHP trial (p<0.01) at T3 of the CSWD trial. The study results verified that IMBV increases as a result of the local thermal effect of CSWD, and also suggest that CSWD is more effective at enhancing IMBV than EHP.

Key words: Shortwave diathermy, Near-infrared spectroscopy, Intramuscular blood volume

INTRODUCTION

Shortwave diathermy is a thermotherapy that uses electromagnetic waves of 27.12 MHz to heat the deep tissues of the human body. There are two modalities used in rehabilitation as therapeutics targeting deep tissues: shortwave diathermy and ultrasound1, 2). Garrett et al. compared the heat conduction of pulsed shortwave diathermy and ultrasound by inserting thermistor thermometers into the triceps surae muscle. They reported that shortwave diathermy induced rises in temperatures over a wide area and was therefore more suitable for the treatment of broader areas than ultrasound3). Shortwave diathermy induces heat generation in the body by influencing internal electric fields and causing eddy currents within tissues4). Some of the thermal effects of shortwave diathermy resulting from the accompanying rise in tissue temperature include increased blood flow, relief from deep muscle pain and spasms5–7), and heightening of the pain threshold3, 8). Animal studies performed to
investigate the relationship between the shortwave diathermy and the blood flow demonstrated a correlation between temperature and blood flow\(^5\). Doraper and Garrett et al. used thermistor thermometers to demonstrate that application of shortwave diathermy (48 W mean output) increased the intramuscular temperature of the gastrocnemius muscle by approximately 4\(^\circ\)C\(^3,9\). A rise in muscle tissue temperature is thought to induce an increase in intramuscular blood flow volume. Evaluation of circulation dynamics within muscle tissues provides important data for the assessment of thermotherapies.

In recent years, near-infrared spectroscopy (NIRS) has often been used to evaluate hemodynamics and oxygen consumption within local muscle tissues\(^10–15\). The application of NIRS in human began clinical settings with the report of Jöbsis in 1977\(^16\). NIRS is based on the relative transmissivity of tissues and the absorption feature of hemoglobin (Hb) in the near-infrared region\(^17\). The maximum measurement depth of NIRS has been reported as roughly half the distance between the light source and the detector\(^18, 19\). NIRS allows non-invasive measurement of relative changes in the concentrations of oxyhemoglobin (oxy-Hb) and deoxyhemoglobin (deoxy-Hb) present in deep tissues and muscle tissues. The concentration of total hemoglobin, which is the sum of oxy-Hb and deoxy-Hb (total-Hb; = oxy-Hb + deoxy-Hb), reflects the blood volume and oxygen consumption in tissues\(^10–15, 17, 20, 21\).

The influence of the electromagnetic waves on sensors or devices are unavoidable during shortwave diathermy, but with NIRS it is possible to eliminate the influences of electromagnetic waves, enabling continuous measurement of the relative changes in Hb concentration in muscle tissues, with an optical fiber cord as the probe of the NIRS device.

The purpose of this study was to elucidate the relationship between continuous shortwave diathermy (CSWD) and circulation dynamics within muscle tissues. Simple and non-invasive evaluation of changes in intramuscular blood volume (IMBV) is a requirement for the establishment of shortwave diathermy treatment guidelines. CSWD was quantitatively compared with the electric hot pack (EHP), as a physical agent for superficial heating.

**METHODS**

**Study design**

A group of subjects receiving no thermotherapy was established as a control group for comparison with the subjects receiving either CSWD or EHP thermotherapy. A time series model for repeated measurements was used, with change in the Hb concentration as an independent variable and changes in intramuscular Hb concentration. The study was designed to compare changes in the oxy-Hb, deoxy-Hb, and total-Hb using three interventions (CSWD, EHP, and control) during the pre-intervention, intervention, and post-intervention periods.

**Subjects**

The study was performed with healthy adults with no history of circulatory disorders of the lower limbs selected from among a group of volunteers who provided informed consent after receiving an explanation of the study outline. Table 1 shows an overview of the study subjects. The subjects consisted of 41 healthy adults (22 females and 19 males) aged 22 to 35 years with heights ranging from 150 to 186 cm, weights ranging from 34.6 to 76.4 kg, and body fat percentages ranging from

<table>
<thead>
<tr>
<th>Table 1: Physical characteristic of subjects</th>
<th>mean ± s.d.</th>
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<tr>
<td>CSWD</td>
<td>EHP</td>
</tr>
<tr>
<td>Numbers</td>
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</tr>
<tr>
<td>Age (years)</td>
<td>27.4</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>166.2</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>57.3</td>
</tr>
<tr>
<td>Body Fat (%)</td>
<td>19.1</td>
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</tbody>
</table>

Twelve subjects participated in the control and EHP trials, and five of these subjects were the same subjects.
9.3% to 39.8%. There were 12 subjects in the control group, 12 subjects in the EHP group, and 17 subjects in the CSWD group. Subjects were instructed to avoid exercising within two hours prior to the start of the trial, to limit their activities to activities of daily living, and to remain at rest during the NIRS measurement.

**Instrumentation**

A 27.12-MHz shortwave diathermy unit (SW-180, Ito Co., Ltd. Japan) with 135° condenser electrodes was used. CSWD was performed using the condenser method with an output of 80 W for 10 min. Two condenser electrodes were placed at proximal and distal sites of the medial head of the gastrocnemius muscle of the right lower leg 2 to 3 cm away from the skin (see Fig. 1 for the positioning of the co-planar electrodes). The output of the shortwave diathermy unit was calibrated by the manufacturer prior to the start of the study. The EHP used was the electric hot pack unit (FA-2, Sakamoto Co., Ltd., Japan) with a far-infrared ceramic sheet (dimensions: L 69 × W 39 × D 1.5 cm). The thermo regulator in the far-infrared ceramic sheet maintains a temperature of 80 degrees Celsius and the surface temperature of the EHP unit is about 50 degrees Celsius, since the far-infrared ceramic sheet is doubly enshrouded by a thick plastic cover and a thick cloth. The EHP was wrapped in a towel and placed on the surface of the skin above the medial head of the gastrocnemius muscle.

The NIRS unit (OM-220, Shimadzu Corp., Japan) was used to measure changes in the Hb concentration. NIRS detects changes in Hb concentration based on the modified Lambert-Beer law. A NIRS probe was attached with elastic tape to the center of the belly of the medial head of the right gastrocnemius muscle so as to maintain a distance of 4 cm between the light source and the detector. The penetration depth of near-infrared radiation is estimated to be approximately 2 cm². NIRS measurement was performed using a sampling time of one second. Measurement data were analyzed with a personal computer (PC). The concentrations were expressed using arbitrary units (AU) since the data obtained by NIRS measurement represent relative changes in concentration.

**Procedures**

Subjects were requested to lie in a prone position on a treatment bed during the NIRS measurement. Initially, changes in Hb at rest were measured for 5 min (pre-intervention). Then, the thermotherapy was performed for 10 min on the subjects in the CSWD and EHP groups (intervention). Additional NIRS measurement was performed continuously for 10 min following the completion of thermotherapy (post-intervention). Subjects in the control group received no thermotherapy and underwent NIRS measurement while they remained at rest (Fig. 2).

For one subject (male) in CSWD group who received CSWD, NIRS measurement was continued until approximately 130 min after the completion of the treatment in order to study the relationship between time factors and changes in IMBV induced by CSWD.

**Statistical analysis**

Analysis was performed on NIRS data obtained in five-minute periods, T1, T2, and T3, the pre-intervention, the latter half of the intervention, and post-intervention periods, respectively (Fig. 2). Time integration was calculated for the oxy-Hb, deoxy-Hb, and total-Hb measured by NIRS during T1, T2, and T3. Comparisons were performed among the CSWD, EHP, and control groups, among
the T1, T2, and T3 intervals, and among oxy-Hb, deoxy-Hb, and total-Hb. Statistical analysis was performed using two-way analysis of variance (two-way ANOVA) with $3 \times 3$ repeated measurements on the change in each Hb parameter and the Tukey post-hoc multiple comparison test, which was performed in order to clarify intergroup differences.

RESULTS

Figure 3 shows the changes in oxy-Hb, deoxy-Hb, and total-Hb for one subject, as representative raw data of the CSWD group. Oxy-Hb and total-Hb increased, beginning five minutes after the start of the CSWD trial and continued to increase for more than 15 min after the completion of treatment. Unlike oxy-Hb and total-Hb, deoxy-Hb only fluctuated within a limited range (0.04). Since it was observed that oxy-Hb was still rising at 25 min, the completion of measurement in the CSWD trials, one subject in the CSWD group was measured by NIRS for 160 min in order to determine how many minutes were required for oxy-Hb to begin to decrease. The data is shown in Fig. 4. As with the data shown in Fig. 3, oxy-Hb and total-Hb increased, but deoxy-Hb showed limited changes. Oxy-Hb and total-Hb peaked approximately 80 min after the completion of CSWD. Both oxy-Hb and total-Hb began to decrease gradually after 95 min, but still remained at concentrations higher than those found at the start of the CSWD trial 160 min after the start of NIRS measurement.

Table 2 shows the integration values of the Hb concentrations calculated for each interval for each group. Two-way ANOVA was performed on the CSWD, EHP, and control groups and the T1, T2, and T3 intervals. The results demonstrate the presence of interaction in the patterns of change of the oxy-Hb integration value ($p<0.01$, $F_4, 76=10.86$) and total-Hb integration value ($p<0.01$, $F_4, 76=15.96$). CSWD increased the oxy-Hb integration value significantly more than either EHP or the control ($p<0.01$). CSWD increased the total-Hb integration value significantly more than either EHP ($p<0.05$) or the control ($p<0.01$). There was no interaction found for the deoxy-Hb integration values ($p>0.05$, $F_4, 76=2.44$).

Hb integration values were compared among groups at the T1, T2, and T3 intervals using the Tukey post-hoc multiple comparison test. At T1,
there were no significant differences in oxy-Hb, deoxy-Hb, and total-Hb among the CSWD, EHP, and control groups. At T2, the integration values of oxy-Hb and total-Hb in the CSWD group were significantly higher compared to the control group (p<0.01), but there were no significant differences in the integration values of oxy-Hb and total-Hb between the CSWD and EHP groups and between the EHP and control groups. There were no significant differences in the integration values of deoxy-Hb among the groups at T2. At T3, the integration values of oxy-Hb and total-Hb in the CSWD group were significantly higher compared to the control and EHP groups (p<0.01 for both groups). There were no significant differences in the integration values of deoxy-Hb among the groups at T2. At T3, the integration values of oxy-Hb and total-Hb in the CSWD group were significantly higher compared to the control and EHP groups (p<0.01 for both groups). There were no significant differences in the integration values of deoxy-Hb among the groups at T2. At T3, the integration values of oxy-Hb and total-Hb in the CSWD group were significantly higher compared to the control and EHP groups (p<0.01 for both groups).

**DISCUSSION**

In this study, NIRS measurement was chosen as a means of studying the circulation dynamics within the medial head of the gastrocnemius muscle during shortwave diathermy because NIRS-based hemoglobin measurement can provide valuable information on IMBV dynamics\(^{12, 13}\). The most important issue affecting the study of shortwave diathermy is the effects of electromagnetic waves. The electromagnetic waves interfere with measurements performed simultaneously during shortwave diathermy, but NIRS resolves this issue with the use of near-infrared light and optical fiber cables. The use of NIRS allowed us to perform continuous measurement of intramuscular circulation dynamics while avoiding the artefacts of electromagnetic waves.

The inductive method is thought to be better suited than the condenser method for use in heating muscle tissues\(^ {24}\). However, the condenser method was used in the present study since the NIRS detection probe had to be attached immediately below the application site during NIRS measurement, and it was thought likely to affect the thermal effects of shortwave diathermy if the inductive method was used.

**Circulatory response in the prone position**

Local circulation within the gastrocnemius muscle while subjects lay in the prone position was measured with NIRS. Oxy-Hb and deoxy-Hb reflect the state of the arterial and venous blood in the local tissues. An increase in oxy-Hb indicates an increase in the volume of fresh blood supplied by the arteries. An increase in deoxy-Hb indicates that oxygen has been supplied to the tissues. Decreased oxy-Hb along with increased deoxy-Hb reflect oxygen metabolism resulting from muscle contraction. Increased blood volume to compensate

<table>
<thead>
<tr>
<th>Table 2. Integration value of Hb in each trial</th>
<th>arbitrary units (AU), mean ± s.d.</th>
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<tbody>
<tr>
<td></td>
<td>CSWD</td>
</tr>
<tr>
<td>Oxy-Hb* T1</td>
<td>4.14 ± 2.02</td>
</tr>
<tr>
<td>T2</td>
<td>13.65 ± 7.68( ^{\dagger})</td>
</tr>
<tr>
<td>T3</td>
<td>28.83 ± 10.65( ^{\dagger})</td>
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<tr>
<td>deoxy-Hb T1</td>
<td>1.62 ± 0.92</td>
</tr>
<tr>
<td>T2</td>
<td>5.54 ± 2.53</td>
</tr>
<tr>
<td>T3</td>
<td>3.34 ± 2.14</td>
</tr>
<tr>
<td>total-Hb* T1</td>
<td>4.21 ± 2.73</td>
</tr>
<tr>
<td>T2</td>
<td>17.65 ± 9.21( ^{\dagger})</td>
</tr>
<tr>
<td>T3</td>
<td>30.62 ± 12.76( ^{\dagger})</td>
</tr>
</tbody>
</table>

Two-way ANOVA performed on the CSWD, EHP, and control groups. *: Interaction (+). The table shows the integration values of each Hb parameter for each intervention. The values shown are the results of multiple comparisons performed on the values of each Hb parameter at the T1, T2, and T3 intervals among the CSWD, EHP, and control groups. ‡: T2 & T3 CSWD > Control (p<0.01). †: T3 CSWD > EHP (p<0.01).
for oxygen debt is observed upon the completion of muscle contraction\textsuperscript{15, 25).} The changes in deoxy-Hb observed in this study occurred within a narrow range since the subjects remained at rest and limited their muscle activity to a level sufficient to maintain their position (Table 2).

An increase in oxy-Hb over time was seen in the control group. Generally, congestion caused by poor circulation in the muscle tissues is one factor responsible for increased oxy-Hb. However, congestion caused by poor circulation is unlikely to be the cause for the increase observed in this study, since none of the subjects had circulatory disorders. Additionally, since measurement was performed with the subjects lying in a prone position, i.e., subjects did not assume positions with the legs pointed downward, such as standing or sitting positions, the occurrence of a congestive state during measurement was unlikely. In a preceding study using NIRS, in which subjects lay in a fixed position on a tilt-table which was gradually inclined from $-10^\circ$ to $75^\circ$ at roughly two-minute intervals, there was no change in oxy-Hb and only a tendency for deoxy-Hb to gradually increase was observed\textsuperscript{10).} This suggests that the change in deoxy-Hb observed in this study was the result of increased venous blood volume caused by an increase in vascular compliance. Similarly, the increase in oxy-Hb seen in the control group of the present study was suspected to be the result of an increase in the vascular compliance of the arterial system induced by the shifting of body position from a standing to a prone position. When subjects lie in a resting, prone position a decrease in the pumping action of the lower leg muscles occurs, that increases the blood volume within the muscle tissues. Furthermore, a decrease in the muscle sympathetic nerve activity along with a change in muscle activity causes the parasympathetic nerve activity to become dominant, which increases the vascular compliance of the arterial system The fact that concentrations did not stabilize until immediately before the completion of the NIRS measurements indicates that the change was a gradual circulatory response. It was reported that circulatory responses induced by pressure changes in the lower limbs affect those of the upper limbs\textsuperscript{23).} In the present study, we consider that changes in the internal abdominal pressure induced by the prone position caused the increase in oxy-Hb observed in the lower leg.

**NIRS measurement**

Figure 3 shows the changes in hemoglobin concentrations seen with CSWD as measured by NIRS. Oxy-Hb and total-Hb began to gradually increase five minutes after the start of CSWD. The increase in total-Hb was a reflection of the increase in oxy-Hb, because deoxy-Hb did not change during CSWD. It was thought that there was an increase in blood volume within the medial head of the gastrocnemius muscle since total-Hb reflects the blood volume. Total-Hb was affected by the increase in oxy-Hb, suggesting that CSWD increased the blood volume supplied from the arteries. Each Hb concentration was reset to zero at the start of NIRS measurement; thus, the measured value is a relative value. While evaluation of the amount of exercise requires measurement of the maximum changes in each Hb, for the evaluation of physical agents, it is important to observe gradual circulatory responses. Accordingly, comparisons were performed based on time integration values. Time integration of changes in concentration per unit time is thought to allow more accurate evaluation of blood volume dynamics.

**Comparison of physical agents**

There were no significant differences in the integration values for each Hb variable at T1 among the CSWD, EHP, and control groups. This finding suggests that the differences found at the T2 and T3 intervals were caused by the effects of the interventions. The significant increase in the oxy-Hb integration value found in the CSWD group compared to the control group at T2 indicates that CSWD increased IMBV (Table 2). The integration values of oxy-Hb tended to be high in the EHP group compared to the control group, but the differences were not significant. Blood volume was significantly higher in the CSWD group compared to the EHP and control groups (p<0.01 for both) at T3 (Table 2).

In previous studies of shortwave diathermy, the muscle tissue temperature was measured during treatment using thermistor thermometers inserted into the muscle tissues\textsuperscript{8, 26).} Draper et al. performed shortwave diathermy on the medial head of the gastrocnemius muscle using the inductive method, pulsed mode, with a mean output of 48 W. Draper’s group found a mean 3.78°C rise in intramuscular temperature after 15 min of treatment compared with the pretreatment temperature, and a mean
1.78°C fall 10 min after treatment. Verrier et al. performed 20 min of shortwave diathermy using the condenser method and the inductive method and compared intramuscular temperature with skin temperature, and found intramuscular temperature rises of 2.24°C and 4.40°C with use of the condenser method and the inductive method, respectively. Unfortunately, since the output used by Verrier et al. was indicated in amperes, direct comparisons with their results were impossible.

In this study, shortwave diathermy was performed with a mean output of 80 W for 10 min using the condenser method. There are differences in the shortwave diathermy performed in this and other reported studies in terms of the mean output and treatment duration. The results of previous studies demonstrate that the intramuscular temperature gradually increases during the intervention, and that this acts as one of the factors causing the gradual increase in IMBV. It was reported that intramuscular temperature remains high compared with pre-treatment and decreases gradually, however, in the present study, IMBV continued to increase after the intervention. Previously, it has been thought that the body increases the blood flow volume in response to an increase in tissue temperature, as a means of maintaining tissue temperature, or to cool the temperature of heated tissues, and the blood flow volume, therefore, changes in parallel with tissue temperature. In this study, however, a circulatory response was observed in which blood volume continued to increase after intervention. This result has interesting implications for the field of shortwave diathermy.

Physiological effects are generally evaluated based on changes in tissue temperature. Lehmann reported that a 1°C rise in tissue temperature mitigates mild inflammation and increases metabolism, a 2°C to 3°C rise reduces pain and muscle spasms, and a 3°C to 4°C or greater rise promotes the extensibility of collagen tissues. Increased blood flow was thought to play a role in the physiological effects of heating, particularly in mitigation of pain and promotion of muscle healing. Elevations in tissue temperature have effects on muscle spasms and increase the extensibility of muscles, thereby improving the range of motion. For clinical applications, the important consideration is to avoid causing patients pain during treatment, and to evaluate blood flow at the treated area. McGray et al. compared hot pack treatment and CSWD at trigger points using a pressure gauge and reported that CSWD was more effective in continuing to relieve pain after intervention. In the present study as well, based on the changes seen in intramuscular Hb concentration, significantly higher blood volumes were maintained following CSWD intervention.

Changes in blood volume over time
The changes in Hb concentration accompanying CSWD were measured for approximately 160 minutes in one subject. The oxy-Hb peaked approximately 80 min after the completion of CSWD and gradually decreased thereafter. Verrier et al. monitored the temperature changes for 30 min after the completion of continuous shortwave diathermy. They reported that the intramuscular temperature gradually fell, but remained higher than the temperature found prior to the start of measurement. Comparison of the results of the present study and the results of previous studies concerning intramuscular temperature suggest that the changes in IMBV seen after shortwave diathermy are not consistent with the changes seen in intramuscular temperature.

A number of mechanisms are involved in the physiological response of increased IMBV. The rise in tissue temperature stimulates the surrounding heat receptors, inducing axonal reflex of the spinal cord and dilation of the vascular smooth muscle, which in turn increases blood volume. Given reports of the vasodilatory and vasoconstrictive effects of the muscle sympathetic nerves in muscle tissues, we suspect that muscle sympathetic nerves may be involved in the regulation of blood flow volume as well. It has also been reported that blood vessels dilate as a result of the transient response of muscle sympathetic nerves to electrical stimulation. There are also reports about differences in the responses to blood flow between the skin sympathetic nerves, which are distributed superficially, and the muscle sympathetic nerves, and the response of the muscle sympathetic nerves during muscle ischemia.

Intramuscular blood flow volume is regulated by these diverse mechanisms, which are further modified in response to various conditions. The autonomic nervous system, including the muscle sympathetic nerves, is likely to play a role in the changes in IMBV seen in the present study. It was
found that the increased blood volume was observed for more than one hour, and that blood volume did not change in conjunction with changes in tissue temperature. These finding suggest that shortwave diathermy not only induces secondary increases in blood flow volume as a result of a rise in intramuscular temperature but also may act directly on the nervous system and the vascular system.

LIMITATIONS

Hicks compared NIRS findings and oxygen saturation of venous blood measured during 10% and 30% maximal voluntary contraction under conditions of hypoxia and normoxia. Hicks suggested caution in the application of non-invasive NIRS measurement since NIRS failed to detect changes at 10% maximal voluntary contraction. NIRS does not provide absolute values, since it measures relative Hb changes. Regardless of these limitations, however, NIRS remains a useful noninvasive method for evaluating thermotherapies as it provides information on relative changes in blood volume.

CONCLUSION

The effects of shortwave diathermy on IMBV were studied. Shortwave diathermy was compared with electric hot pack treatment and without treatment (control) and the differences were evaluated. While deoxy-Hb remained nearly constant, oxy-Hb increased and caused an increase in total-Hb. This finding suggests that the increased IMBV was supplied by the arterial system. This increased IMBV is suspected to reflect an increase in the volume of blood flow in the tissues. The effect of shortwave diathermy to increase IMBV was demonstrated by non-invasive NIRS measurement. The results of this study are consistent with hypotheses presented in previous studies and demonstrate that shortwave diathermy therapy is a more effective thermotherapy than electric hot pack treatment for increasing blood volume.

REFERENCES

18) Cui W, Kumar C, Chance B: Experimental study of migration depth for photons measured at sample


