Circulatory Response of Digital Arteries Associated with Electrical Stimulation of Calf Muscle in Healthy Subjects

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The purpose of this study was to investigate the effects of electrical stimulation (2,500-Hz sine wave modulated at 50 bursts per second) of the posterior calf musculature on the blood circulation of an unexercised part of the body, the ipsilateral digital arteries. Intensities of electrical stimulation sufficient to produce 15% and 30% of isometric maximum voluntary contraction (MVC) of the plantar flexor muscles were used. Twenty-four healthy subjects participated in this study and were assigned either to an Experimental Group receiving electrical stimulation (n = 13) or to a Control Group not receiving electrical stimulation (n = 11). Analysis of data revealed significant differences in finger blood flow when the calf musculature was stimulated electrically. We found significant differences in blood flow of the finger when torques produced by electrical stimulation of the calf musculature were raised to 15% and 30% of MVC. The results of the study indicate that blood flow in the ipsilateral finger decreases significantly when the posterior calf musculature is exercised artificially with electrical stimulation bursts.

Key Words: Blood circulation, Electric stimulation, Physical therapy.

Voluntary exercise causes circulatory changes to occur in nonexercising parts of the body. Diversion of blood flow from the nonexercised parts of the body to voluntarily exercised muscle is well established. Whether low frequency electrical stimulation (2,500-Hz sine wave modulated at 50 pulsed bursts per second) producing graded muscular responses affects blood flow of an unexercised part of the body is unknown.

Blair et al found a small increase in blood flow to the muscles of the forearm of untrained individuals who performed light exercises of the lower extremities, although blood flow to the skin of the forearm remained unchanged. Bevegard and Shepherd reported a transient increase in forearm blood flow and a decrease in arterial blood pressure with the onset of lower extremity exercise. The forearm blood flow remained at the preexercise level during moderate volitional exercise, but blood flow decreased when heavy exercise was introduced. Zelis et al reported that in healthy subjects performing mild lower extremity exercise, forearm muscle blood flow did not change significantly, but with moderate and strenuous activity of the lower extremities, forearm blood flow was reduced significantly. In a recent study, Kitamura et al demonstrated that finger blood flow decreased rapidly immediately after the onset of lower extremity exercise and remained at reduced levels throughout the exercise. Their results, however, indicated that the amount of decrease in finger blood flow during exercise was independent of exercise intensity.

For some time, electrical stimulation of muscle has been used to study muscle metabolism and kinetics. Merton and Naess and Storm-Mathisen clearly demonstrated that the force elicited by maximum voluntary contractions (MVCs) and by electrical stimulation of muscles were the same. Rhythmic muscular contractions produced by electrical stimulation increase peripheral circulation in a fashion similar to voluntary contraction.

Wakim studied the influence of various frequencies of continuous direct electrical stimulation (4-256 Hz) on the blood flow in the stimulated extremity of the dog. He found that 16 pulses per second (pps) caused the greatest increase in blood flow to the exercised muscle, whereas higher frequencies (64, 128, and 256 Hz) resulted in much smaller increases in blood flow. Additionally, he reported that at various times during stimulation, the blood flow in the nonexercised leg increased, decreased, or was identical to the preexercise blood flow. He concluded, however, that electrical stimulation produced an overall decrease in blood flow in the unstimulated extremity.

Currier et al, using 2,500-Hz sine waves interrupted at 50 pulsed bursts per second that produced fused tetanic muscular contractions, reported an increase in blood flow to the stimulated muscle. This study represents results obtained from "new generation" electrical stimulators about which little is known concerning their effects on blood circulation. The
electrical current characteristics of these stimulators have been promoted for augmenting muscular strength.\textsuperscript{10,11} Electrical stimulation is being accepted clinically by physical therapists as a means to increase the strength of healthy muscles. Most research on the effects of electrical stimulation on circulation, however, has not involved the type of state-of-the-art stimulator that we have used. The purpose of this study, therefore, was to investigate the effects of electrical stimulation (2,500 Hz modulated at 50 bursts per second) on the blood flow of an unexercised part of the body using current intensities sufficient to produce muscle contractions of 15% and 30% of MVC. We hypothesized that electrical stimulation of the right posterior calf muscle would not alter the circulation of the digital arteries in the ipsilateral long finger.

**METHOD**

**Subjects**

Twenty-four healthy volunteer subjects (5 men, 19 women) with normal heart rates and blood pressures, ranging in age from 20 to 28 years, participated in this study. All subjects signed an informed consent statement after being briefed on the purpose, procedures, and risks of the study. Subjects were assigned randomly to either the Experimental Group (n = 13) or the Control Group (n = 11). Table 1 gives the demographic information of these subjects.

**Measurement of Ankle Torque**

The Experimental Group subjects were measured for MVC of the plantar flexor musculature while the results were recorded using an isokinetic dynamometer\textsuperscript{*} interfaced with a multichannel graphic recorder\textsuperscript{†} (damping set at 1). The Experimental Group executed three isometric MVCs with a rest period of two minutes between trials. The highest torque value of the three contractions was used as the subjects' MVC. Torque measurements were obtained from all subjects who were positioned prone on a test table with their right foot secured to the lever arm of the dynamometer. The test leg was secured to the dynamometer at the foot (0° dorsiflexion) with webbed straps, and the knee was secured similarly to the table ensuring stability during the torque measuring procedure. The arms of the subjects were placed at their sides, and they were told not to use hand support during the MVC tests. The trunk was unsupported during exertion in order to minimize assistance from body musculature other than the calf muscles. The dynamometer was set for 0°/sec to obtain an isometric torque reading.

Immediately after measuring the voluntary torque produced by the calf musculature, we determined the current intensity required to produce electrically isometric torques equal to 15% and 30% of each Experimental Group subject's measured voluntary isometric MVC. We used these predetermined current intensities, specific to each Experimental Group subject, to induce isometric muscle contractions during the experimental procedure. Table 2 shows the group descriptive data of torque and current intensity determinations.

**TABLE 1**

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (yr)</th>
<th>Weight (kg)</th>
<th>Height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (n = 11)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \bar{x} )</td>
<td>25.6</td>
<td>57.9</td>
<td>163.2</td>
</tr>
<tr>
<td>Range</td>
<td>20-30</td>
<td>51.4–68.2</td>
<td>157.5–182.9</td>
</tr>
<tr>
<td>( s )</td>
<td>3.2</td>
<td>5.6</td>
<td>7.4</td>
</tr>
<tr>
<td>Experimental (n = 13)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \bar{x} )</td>
<td>25.8</td>
<td>62.9</td>
<td>169.7</td>
</tr>
<tr>
<td>Range</td>
<td>20–36</td>
<td>48.8–77.3</td>
<td>157.0–186.7</td>
</tr>
<tr>
<td>( s )</td>
<td>6.0</td>
<td>10.6</td>
<td>8.4</td>
</tr>
</tbody>
</table>

**TABLE 2**

<table>
<thead>
<tr>
<th>Group</th>
<th>Active Isometric Torques (N·m)</th>
<th>Current Intensities (mA) to Produce 15% MVC</th>
<th>30% MVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (n = 11)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \bar{x} )</td>
<td>72.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>50.1–109.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( s )</td>
<td>16.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental (n = 13)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \bar{x} )</td>
<td>59.1</td>
<td></td>
<td>15.5</td>
</tr>
<tr>
<td>Range</td>
<td>32.5–89.4</td>
<td>9.5–17.0</td>
<td>12.0–25.0</td>
</tr>
<tr>
<td>( s )</td>
<td>15.6</td>
<td>2.5</td>
<td>4.0</td>
</tr>
</tbody>
</table>

**Measurement of Heart Rate, Blood Pressure, and Finger Blood Flow**

Subjects rested in a prone position on a treatment table for about 15 minutes while prestimulation preparations and recordings were made. Heart rate was measured by palpation of the right radial artery (pulse), and blood pressures were measured with a sphygmomanometer and auscultation of the right brachial artery. These baseline heart rates and blood pressures were obtained before MVC and percentage contractions were determined. A second set of heart rate and blood pressure measurements was made at the conclusion of the experiment.

The blood flow of the ipsilateral third digital artery of each subject was assessed using a dual-frequency, continuous wave, ultrasonic directional Doppler device (Model 909, 5.3 MHz).\textsuperscript{‡} The subjects' right arm was rotated laterally (externally) with the elbow slightly flexed, forearm pronated, and the hand and wrist maintained in a resting position. The Doppler signal was calibrated before the measurement sessions of the experiment. The room temperature was maintained at 22°C (72°F). The Doppler ultrasonic device was connected to the multichannel graphic recorder to transcribe the blood flow signals of the artery. The pencil probe of the Doppler was positioned on the skin (coupled with conductive gel) over the volar surface of the third digit of the right hand (immediately distal to the metacarpal head) and moved to the angle and point at which the loudest, highest-pitched frequency shift from the

\* Cybex, Div of Lumex, Inc, 2100 Smithtown Ave, Ronkonkoma, NY 11779.

† Model R612, Beckman Instruments, Inc, 3900 River Rd, Schiller Park, IL 60176.

‡ Parks Medical Electronics, Inc, Beaverton, OR 97075.
artery was audible over the loudspeaker of the ultrasonic device. The probe position then was maintained by a clamp throughout the experiment. For each measurement, a tracing containing 20 to 25 consecutive analog signals (each representing a complete cardiac cycle) was transcribed on the multichannel recorder. Doppler measurements were obtained in both groups during the prestimulation rest period (t = 0); at intervals of 1, 5, and 10 minutes between electrical stimulation cycles (t = 1, 5, and 10); and at intervals of 1, 3, and 5 minutes after electrical stimulation was terminated (t = 11, 13, and 15).

**Electrical Stimulation Procedure**

An Electrostim 180-2§ stimulator provided the electrical stimuli to produce tetanic isometric contractions of the right calf musculature of the subjects in the Experimental Group. The stimulator produced individual sine waves at a frequency of 2,500 Hz in modulated bursts at a rate of 50 bursts per second. The timing sequence used in this study produced a 12-second output burst followed by an 8-second rest period (12:8 duty cycle). The bursts of stimuli had an intensity that was finely ramped (surged) so that peak voltage of each series of bursts increased gradually over a 2-second period and was sustained for 10 seconds. At the end of the 12-second stimulation period, the intensity declined abruptly and was followed by the 8-second rest period before the next stimulation cycle began.

One stimulator electrode (6.2 x 6.2 cm, flexible rubber) was placed over the motor point of the medial belly and a similar electrode was placed over the motor point of the lateral belly of the gastrocnemius muscle. The electrodes were secured to the lower leg by Velcro straps. The subjects were positioned prone with the ankle in neutral and the plantar surface of the foot stabilized against a rigid barrier. The first series of electrically induced isometric contractions and measurements were recorded at the predetermined intensity to produce isometric torque equivalent to 30% of MVC. After completion of the 5-minute poststimulation (t = 15) blood flow measurement (30% MVC), heart rate and blood pressure measurements were obtained again.

Control Group subjects underwent conditions (position, electrode locations, and connections) and measurements (heart rate, blood pressures, finger blood flow, and torque) similar to those of the Experimental Group subjects but without electrical stimulation.

**Data Analysis**

We used the pulsatility index (PI) to analyze blood flow to the stimulated muscle. We calculated the PI using the following formula:

\[
PI = \frac{PP}{MD}
\]

where \(PP\) is the peak-to-peak signal size, and \(MD\) is the mean distance between signals averaged over several cardiac cycles. The mean peak amplitudes and mean cardiac cycle times (PP/MD) of each subject’s centermost 15 cycles of 20 to 25 consecutive signals from each subject recorded at t = 0 to t = 15 were used in the analysis. Each PI value used in the blood flow analysis represents the mean of 15 analog signals recorded in each group of recorded signal tracings. A multivariate analysis of variance (MANOVA) was used to examine the group and time differences among the dependent variables (i.e., heart rate, systolic blood pressure, and diastolic blood pressure) and the interaction differences between time (prestimulation, poststimulation) and group (Experimental, Control). A 2 (groups) x 2 (percentage of MVC) x 7 (measurement intervals) univariate ANOVA for repeated measures was used to examine each subject’s PI as the dependent variable served to assess the effects of electrical stimulation. The groups were Experimental and Control; the percentages of MVC were 15% and 30%; and the intervals of measurement were t = 0, 1, 5, 10, 11, 13, and 15 minutes. Mean prestimulation values between the Experimental and Control Groups were examined by an independent t test (two-tailed) to determine equality between groups. Analysis of the mean prestimulation (t = 0) heart rate, blood pressure, and PI values showed that the groups were matched similarly on these variables before experimental intervention. Thus, no adjustments were made in the statistical analyses. A 5% probability level for significance \((p < .05)\) was applied for all statistical tests.

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§ Micromed Instruments, Inc, 225 Migneron, St. Laurent, Quebec, Canada H4T 1W8.

significant differences were found, the Newman-Keuls test was applied to discern which means of a treatment array were significantly different.

RESULTS

We found no significant differences between the Experimental and Control Groups based on their mean prestimulation (t = 0) heart rate, blood pressure (systolic and diastolic), and PI values. Table 3 presents a summary of the prestimulation and poststimulation heart rate and blood pressure data.

Table 4 shows that heart rates and blood pressures were unaffected between the Experimental and Control Groups, between the designated prestimulation and poststimulation time periods, and within the time-by-group interaction. The one exception among the nonsignificant dependent variables from the multivariate analysis was the statistically significant time-by-group interaction for heart rate.

Blood flow data of this study are presented in Table 5 and Figures 1 through 3. Findings show that the independent variables of group (Experimental Group vs Control Group) and time (specific measurement intervals) had significant influence on the outcomes of this study. Electrically induced contractions of calf musculature were effective in altering blood flow in the third digital artery of the ipsilateral upper extremity in the Experimental Group compared with the Control Group. That is, in the Experimental Group, the Neuman-Keuls test indicated that the mean PIs decreased significantly at intervals of 1, 5, and 10 minutes (t = 1, 5, and 10) during the stimulation period producing torques equal to both 15% and 30% of MVC (Figs. 1, 2). No statistical differences in mean PIs occurred between experimental conditions of 15% or 30% of MVC (Figs. 1, 2). No statistical differences in mean PIs occurred between experimental conditions of 15% or 30% of MVC except at intervals t = 5 and 15 minutes (Fig. 3). No significant differences in mean PIs were revealed between the Experimental and Control Groups at intervals t = 0, 10, 11, or 13 minutes.

DISCUSSION

The experiment had no significant effect on the blood pressures of the subjects. Electrical stimulation to the calf musculature of one leg did not influence either the systolic or diastolic blood pressures of the Experimental Group subjects. Significant time-by-group interaction for heart rate implies that some subjects in the Experimental Group had decreased heart rates throughout the experiment. Because the heart rates of the Experimental and Control Groups were statistically equal before the intervention, the reduction of heart rate in the Experimental Group subjects could be attributed to their reduced anxiety about the electrical stimulation experience. Because the change in heart rate was not accompanied by blood pressure fluctuations, the affected heart rate may be due to chance rather than anxiety. A change in heart rate also was observed in another study of electrical stimulation on blood flow. 9

The main effects and those of interaction appear to be significantly related in this study. The poststimulation (t = 11-15) digital blood flow of the Experimental Group's nonexercised extremities returned to the prestimulation (t = 0) level after a stimulus intensity of 15% of MVC, but with a stimulus intensity of 30% of MVC the blood flow remained increased at five minutes poststimulation (t = 15). This observation of blood flow behavior in the digital artery of a nonexercised extremity differs from that reported previously for blood flow behavior to the muscle being stimulated electrically. 9 In the electrically stimulated muscle, no significant increase in poststimulation blood flow was reported, 9 although in our study the stimulus intensity of 30% of MVC resulted in a rapid increase in blood flow during the 3- to 5-minute poststimulation (t = 13 and 15) intervals. The data of our study imply that the electrical stimulation intensity may affect the blood flow of the ipsilateral nonexercised extremity. This finding of graded stimulus intensity influencing the blood flow of the ipsilateral nonexercised extremity agrees with the work of Littell. 13

Our finding of a sudden drop in finger blood flow during the first minute of muscle contractions at both the 15% and 30% of MVC contraction levels is in agreement with the
results of others. Kitamura et al reported that finger blood flow decreased rapidly immediately after the onset of volitional exercise of the lower extremity and throughout the exercise.5 Blair et al, measuring forearm blood flow during leg exercise, demonstrated an increase in vascular tone of the forearm vessels that was proportional to the intensity of the exercise. The vasoconstriction was attributed to sympathetic fibers supplying the vasculature.2 Bishop et al14 and Muth et al,15 in contrast, reported no change in blood flow to inactive muscles during volitional exercise, but Muth et al suggested that muscle blood flow might decrease with more stressful exercise. Zelis et al reported that forearm muscle blood flow decreased significantly during moderate and strenuous intensities of leg exercise.4 Based on this evidence, vasoconstriction appears to be mediated by the sympathetic nervous system and occurs in the nonexercised limbs after minimal exercise of an isolated body part. Wallin et al could not correlate nerve activity with vasodilation,16 which supports studies that cite sympathetic vasoconstrictors as the major regulatory agents of blood flow in nonexercised muscles during exercise.17,18 Littell analyzed the behavior of vasoconstrictor muscle fibers at the beginning and end of exercise and concluded that increases in activity of the sympathetic vasoconstrictor fibers of nonexercised muscles are the result of peripheral stimuli (reflex responses to exercise) rather than of concurrent cortical activation of the sympathetic system and skeletal muscles.13 The increase in sympathetic vasoconstrictor activity results in a graded decrease in blood flow to the inactive muscles proportional to the work load. This sympathetic nervous system activity shunts part of the cardiac output to the active muscles and skin circulation. The need to dissipate the excess heat generated by the increased metabolic activity of the exercised muscles causes the increase in skin blood flow.2,3,14,15 The vasodilatation of the exercised region is thought to be caused by sensitivity of the vessels to locally accumulated metabolites.19 This vasodilatation effect appears to be independent of sympathetic activity. This independence was demonstrated by Remensnyder et al who found that vessels in the active muscles of dogs were relatively immune to sympathetic stimulation.20

In the vessels of the hand, response to exercise is a balance between a reflex increase in constrictor muscle tone secondary to the exercise and a reflex decrease in constrictor muscle tone caused by the rise in body temperature.21 At the onset of exercise, vasoconstriction predominates and blood flow to the hand decreases. As exercise continues, the blood flow to the hand increases but still is opposed by the reflex constriction induced by the exercise. Numerous researchers have found that blood flow to the hand decreases during leg exercise.2,5,14,15 A similar observation was found in our study between the Experimental and Control Groups that exhibited no significant difference during prestimulation, stimulation, and poststimulation periods. Considerable variation exists between the methodology of our investigation using electrically induced contractions versus other studies that used voluntary muscle contractions. Most studies used bicycle ergometers to exercise the entire leg, whereas our study involved only the calf musculature. Although the percentage of MVC isometric torque elicited by voluntary contraction and by electrical stimulation of muscle is the same, physiological changes such as altered heart rate and blood pressure associated with voluntary exercise6,16 were not observed in our Experimental Group. Further research is needed to determine whether voluntary exercise and exercise by electrical stimu-
lation of equal torque production affect skin blood flow similarly.

Electrical stimulation has been used to reduce circulatory stasis to prevent venous thrombosis and pulmonary embolus. Electrical stimulation is used often in the management of soft tissue injuries in which increased blood flow is desirable. In either condition, the physical therapist applies the electrical stimulation to the involved muscle to improve local circulation. Although the blood flow to the stimulated muscle may increase, the results of this study suggest that the increased local circulation appears to be at the expense of circulation elsewhere in the body. Physical therapists should be aware that the electrically induced form of exercise may have remote circulatory effects similar to those produced by volitional exercise.

Physical therapists also should be aware that activation of the calf musculature does not appear to alter the heart rate and blood flow pressures of subjects receiving low intensity electrical stimulation. Because the absence of exercise-induced vasoconstriction has been reported to limit the volume of blood available to support the increased cardiac output required during exercise and because electrical stimulation simulates voluntary exercise by altering blood flow, caution should be observed with patients with impaired innervation of peripheral vasculature.

CONCLUSIONS

Electrical stimulation having current characteristics of 2,500-Hz sine waves modulated at 50 bursts per second at an intensity sufficient to produce 15% or 30% of isometric MVC torque of the calf musculature of one leg produces a decrease in finger blood flow in the ipsilateral hand and decreases the blood flow in the artery of the third digit within the first minute of electrical stimulation. Finally, blood flow remains below the resting level of flow throughout the interval in which isometric muscle contractions equal to 15% and 30% of MVC are produced by electrical stimulation.

REFERENCES