Research Report

# Effect of Burst-Mode Transcutaneous Electrical Nerve Stimulation on Peripheral Vascular Resistance

Background and Purpose. Based on changes in skin temperature alone, some authors have proposed that postganglionic sympathetic vasoconstrictor fibers can be stimulated transcutaneously. Our goal was to determine the effects of low-frequency (2 bursts per second), burst-mode transcutaneous electrical nerve stimulation (TENS) on calf vascular resistance, a more direct marker of sympathetic vasoconstrictor outflow than skin temperature, in subjects with no known pathology. Subjects. Fourteen women and 6 men (mean age=31 years, SD=13, range=18–58) participated in this study. Methods. Calf blood flow, arterial pressure, and skin temperature were measured while TENS was applied over the common peroneal and tibial nerves. Results. Blood flow immediately following stimulation was not affected by TENS applied just under or just above the threshold for muscle contraction. Transcutaneous electrical nerve stimulation applied at 25% above the motor threshold caused a transient increase in calf blood flow. Regardless of stimulation intensity, TENS had no effect on arterial pressure; therefore, calf vascular resistance decreased only during the trial that was 25% above the motor threshold. Regardless of stimulation intensity, TENS failed to alter dorsal or plantar skin temperature. Discussion and Conclusion. These results demonstrate that the effects of TENS on circulation depend on stimulation intensity. When the intensity was sufficient to cause a moderate muscle contraction, a transient, local increase in blood flow occurred. Cooling of the dorsal and plantar skin occurred in both the stimulated and control legs, most likely because skin temperature acclimatized to ambient room temperature, rather than because of any effect of TENS on circulation. The data, therefore, call into question the idea that postganglionic sympathetic efferent fibers are stimulated when TENS is applied at clinically relevant intensities to people without symptoms of cardiovascular or neuromuscular pathology. [Sherry JE, Oehrlein KM, Hegge KS, Morgan BJ. Effect of burst-mode transcutaneous electrical nerve stimulation on peripheral vascular resistance. *Phys Ther.* 2001;81:1183–1191.]

**Key Words:** *Electrical stimulation, Physical therapy, Regional blood flow, Sympathetic nervous system, Vascular resistance.*

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Transcutaneous electrical nerve stimulation (TENS) is typically used for alteration of pain perception.[1,2] Several investigators,[3–8] however, have reported that TENS can affect the peripheral vascular system. Wong and Jette[5] reported that 3 forms of TENS applied at the motor threshold that result in muscle contractions (high frequency=85 pulses per second [pps], low frequency=2 pps, and burst mode=2 bursts per second [bps]) decreased blood flow in subjects with no known pathology. In contrast, Kaada[6] reported that low-frequency (2–5 pps) and burst-mode (2 bps) TENS, applied over peripheral nerves with intensities high enough to produce visible muscle contractions, increased blood flow in patients with diabetic polyneuropathy and Raynaud phenomenon. Based on changes in skin temperature alone, the investigators in both studies hypothesized that TENS alters vasoconstrictor activity in sympathetic nerves. These investigators, however, did not directly measure sympathetic activity or calculate vascular resistance. More recent studies[7,8] have demonstrated that TENS increases both skin temperature and skin blood flow in subjects with no known pathology and in patients with chronic leg ulcers. Unfortunately, these authors did not report whether the stimulation elicited a muscle contraction; therefore, the potential mechanism underlying their results is difficult to ascertain.

The question of whether sympathetic nerve fibers in peripheral nerves can be stimulated transcutaneously was addressed in a recent study[9] in which continuous-mode, high-frequency TENS (110 pps) was applied over the peripheral nerves of subjects with no known pathology at levels just above and just below the motor threshold. Indergand and Morgan[9] demonstrated that TENS, applied in this manner, does not alter skin leg blood flow or vascular resistance in the leg, or skin temperature, suggesting that sympathetic vasoconstrictor fibers are not activated during transcutaneous stimulation. It is possible, however, that the mode of TENS used (ie, continuous-mode, high-frequency stimulation at 110 pps) failed to cause vasoconstriction because of the nonphysiologic pattern of stimulation. Naturally occurring sympathetic action potentials occur in bursts rather than in continuous trains.[10] Studies using direct nerve stimulation in experimental animals have demonstrated that vascular smooth muscle is more responsive to irregular bursts of stimulation ranging from 2 to 5 bps than to continuous stimulation with the same average stimulation frequency.[11,12]

Burst-mode TENS stimulates peripheral nerve fibers using relatively high carrier frequencies (80–100 pps), modulated burst frequencies (2–5 bps), and intensities above or below the motor threshold.[13] This pattern of external stimulation more closely mimics physiologic sympathetic nerve activity than continuous-mode high- or low-frequency stimulation does. The purpose of our study, therefore, was to investigate the effects of burst-mode TENS on calf blood flow, arterial pressure, and skin temperature in subjects with no known pathology.

## Methods

### *Subjects*

Twenty adults, 6 men and 14 women (mean age=31 years, SD=13, range=18–58 years), served as subjects. All subjects said that they were nonsmokers, were not

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KM Oehrlein and KS Hegge were physical therapist students at the University of Wisconsin-Madison at the time this research was conducted.

This work was performed in partial fulfillment of the degree requirements for Ms Sherry's Master of Science degree in kinesiology at the University of Wisconsin-Madison.

All authors provided writing and data collection. Ms Sherry and Dr Morgan provided research design. Ms Sherry, Ms Oehrlein, and Ms Hegge provided data analysis. Ms Sherry provided project management, and Dr Morgan provided facilities/equipment and consultation. Patricia Mecum provided secretarial assistance, and Nick Puleo provided technical assistance in the laboratory.

The study was approved by the Human Subjects Committees of the Center for Health Sciences, University of Wisconsin-Madison, and the Middleton Memorial Veterans Administration Hospital.

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currently using prescription medications, and did not have a pathology such as neuromuscular or cardiovascular disease. All subjects provided informed consent prior to participation.

### General Procedures

Subjects were studied in a supine position, at least 2 hours after a meal, in a temperature-controlled laboratory (24°±1°C). This was done in an effort to minimize the potential effects of digestion or thermoregulatory activity and to create a stable hemodynamic state. All variables were measured continuously throughout all trials. Blood pressure was measured at 1-minute intervals using an automated sphygmomanometer (Dinamap model 1846 SX/P*).

In order to detect transient blood pressure changes that could influence blood flow, beat-by-beat arterial pressure was also measured by photoelectric plethysmography (Finapres model 2300†). Calf blood flow was measured by venous occlusion plethysmography (model 271 plethysmograph‡) every 15 seconds during baseline and recovery periods. We were unable to record blood flow measurements during the stimulation period because the electrically stimulated muscle contractions affected the stability of the strain gauge–derived plethysmographic tracing. Other details concerning the methods, rationale, and assumptions for venous occlusion plethysmography have been published previously.[14,15]

Skin temperature was measured every minute with a temperature monitor§ and 5-mm-diameter thermistor probes§ placed 2.54 cm (1 in) proximal to the first metatarsal head on both the dorsal and plantar aspects of both feet. These areas of skin are innervated by the peroneal and tibial nerves, respectively.[16] Skin temperature and calf blood flow were measured from both legs simultaneously; therefore, the unstimulated right leg served as a concurrent control during the TENS applications. Because respiratory factors such as hypoventilation, hyperventilation, and the Valsalva maneuver are known to alter sympathetic outflow, vascular resistance, and arterial pressure,[17,18] the subjects were instructed to maintain a stable breathing pattern throughout the data collection period. In this study, a *stable breathing pattern* was defined as the absence of sustained changes in rate or depth of breathing as well as constant end-tidal $CO_2$ levels. To ensure adherence to this instruction, respiration was monitored throughout all trials using a bellows pneumograph‖ wrapped around the abdomen at the level of the diaphragm. In addition, breath-by-breath end-tidal $CO_2$ was monitored by a nasal cannula and capnometer (model 8800#).

The physiologic variability of blood flow, blood pressure, and end-tidal $CO_2$ measurements was assessed by calculating the coefficients of variation ([standard deviation/mean] × 100) for repeated measurements made under baseline conditions. This provided us with an estimate of baseline physiologic variability against which we could compare the effects of TENS. The mean values for the coefficient of variation were 14.9% for leg blood flow, 2.6% for blood pressure, and 5.1% for end-tidal $CO_2$ measurements. Reliability was not determined using standard statistical methods.

### Transcutaneous Electrical Nerve Stimulation

Prior to electrode placement, the skin was cleansed with alcohol, and the course of the tibial and peroneal nerves was mapped out with a 2-channel portable electrical stimulator (Eclipse model 7723**) equipped with a handheld probe. During the nerve mapping, the stimulation intensity was turned up until a muscle contraction was visible. Optimal electrode placement was confirmed by determining the location of the most vigorous contraction. Then, 2 self-adhesive gel electrodes†† (Comfort Ease 5- × 6.4-cm disposable, pin-connector, polymer-gel electrodes) were placed over the tibial and peroneal nerves. A shared dispersive electrode (10- × 5-cm carbon-rubber electrode) was placed on the posterior calf, approximately 9 cm above the calcaneus. Thus, one channel was used to stimulate the tibial nerve and the other channel to stimulate the peroneal nerve. Constant current output with a balanced, biphasic asymmetrical waveform was used. Prior to this study, this waveform was verified by an oscilloscope in our laboratory by the lead author. A burst frequency of 2 bps, a carrier frequency of 85 pps, and a phase duration of 250 microseconds were used. All measurements, except those made with the automated blood pressure cuff, were continuously recorded on a chart recorder (model TA4000‡‡) with a paper speed of 2.5 mm/s. In addition, analog signals were digitized (model 3000A PCM recording adaptor§§) at a rate of 128 Hz with 12-bit resolution and saved on magnetic tape (model HR-D860U videocassette recorder‖‖).

### TENS Protocols

While resting in a supine position with the hips and knees flexed to approximately 70 degrees, each subject

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‡ Parks Medical Electronics Inc, PO Box 5669, Aloha, OR 97006.
§ YSI Inc, 1725 Brannum Ln, Yellow Springs, OH 45387.
‖ Lafayette Instrument Co Inc, 3700 Sagamore Pkwy N, PO Box 5729, Lafayette, IN 47903.
# Sims BCI Inc, N7 W22025 Johnson St, Waukesha, WI 53186.
** Medtronic Inc, 710 Medtronic Pkwy NE, Minneapolis, MN 55432.
†† Empi Inc, 599 Cardigan Rd, St Paul, MN 55126.
‡‡ Gould Inc, 3631 Perkins Ave, Cleveland, OH 44114.
§§ AR Vetter Co, Box 143, Redersburg, PA 16872.
‖‖ JVC Company of America, 41 Slater Dr, Elmwood Park, NJ 07407.

underwent 3 separate trials of 5 minutes of burst-mode TENS. During one trial TENS was just below the motor threshold (ST), in another trial TENS was just above the motor threshold (MT), and in another trial TENS was 25% above the motor threshold (125% MT). The *motor threshold* for each nerve was defined as the analog reading on the electrical stimulator at the lowest intensity that elicited a visible muscle contraction. For the ST trial, the intensity was first increased to the motor threshold, then decreased until the muscle contraction disappeared. For the 125% MT trial, the TENS analog output necessary for motor threshold stimulation was multiplied by 1.25. We believe this method provided us with a way to easily reproduce the relative intensity of stimulation provided from subject to subject. We deemed this method to be appropriate because the TENS unit analog intensity scale and current output were found to be linearly related across all stimulation intensities. Order of the trials was randomized by a balanced Latin square design.[19] Each 15-minute TENS protocol included 5 minutes of baseline data collection, 5 minutes of electrical stimulation, and 5 minutes of recovery data collection. A 10-minute rest period was given between each trial to ensure adequate return to steady state.

### Static Handgrip Protocol

In order to verify that the right and left legs would respond to a known vasoconstrictor stimulus, each subject performed 2 minutes of static handgrip exercises at 30% of his or her predetermined maximal voluntary contraction. The trial consisted of a 2-minute baseline period, a 2-minute handgrip period, and a 2-minute recovery period. We believe that this trial also verified that our instruments were sensitive enough to record subtle changes in leg blood flow.

### Data Analysis

*TENS trials.* Minute values of arterial pressure obtained by the automated sphygmomanometer were converted to mean arterial pressure (MAP) by the following formula[20]:

$$MAP = diastolic\ BP + [(systolic\ BP - diastolic\ BP)/3]$$

MAP values taken simultaneously with blood flow measurements were used in all calf vascular resistance calculations. Calf vascular resistance was calculated by the following formula[20]:

$$Calf\ vascular\ resistance = MAP/calf\ blood\ flow$$

Because we were unable to take calf blood flow measurements during the electrically induced muscle contractions, we compared blood flow measurements immediately before and immediately after stimulation. For each leg, the change in calf blood flow immediately after 5 minutes of stimulation was computed by subtracting the final 30 seconds of baseline measurement from the first 30-second interval of recovery. In addition, in order to determine how long this change persisted, the change in calf blood flow was computed by subtracting the measurement of blood flow during the final 30 seconds of baseline from the measurement taken during the second 30 seconds of recovery. Once the overall change was determined, a paired $t$ test was used to compare the left (stimulated) and right (unstimulated, control) legs.[19] This procedure was repeated for calf vascular resistance (Tab. 1).

The change in MAP was calculated by subtracting the pressure measurement obtained during the final minute of the baseline period from both the pressure measurement obtained during the final minute of stimulation and the pressure measurement obtained during the first minute of recovery. Then, a paired $t$ test[19] was used to compare the difference between these 2 time periods (Tab. 2).

Skin temperature measurements were recorded from each of the 4 sites every minute. For each leg, the change in dorsal and plantar skin temperature from the final minute of the baseline period to the final minute of stimulation was computed. Paired $t$ tests were used to compare the left (stimulated) and right (control) legs for dorsal and plantar regions.[19] To ensure that there was not a delayed effect, this process was repeated to compare the change in skin temperature from the final minute of the baseline period to the first minute of the recovery period.

*Static handgrip trial.* For each leg, changes in arterial pressure, calf blood flow, and calf vascular resistance over time were calculated by subtracting the measurement obtained during the final 30 seconds of the handgrip trial and the final 30 seconds of the recovery period from those obtained during the baseline period. These values were then compared by a paired $t$ test.[19] In all text and figures, data are presented as means $\pm$ standard deviation. Probability values of less than .05 were considered statistically significant.

## Results

### TENS Applications

Burst-mode TENS applied at an intensity 25% above the motor threshold caused a transient increase in calf blood flow and a decrease in vascular resistance in the stimulated leg, but not in the unstimulated control leg. These changes returned to baseline within 1 minute after the

**Table 1.**
Hemodynamic Responses to Submotor Threshold (ST), Motor Threshold (MT), and 25% Above Motor Threshold (125% MT) Transcutaneous Electrical Nerve Stimulation (TENS) in the Left (Stimulated) and Right (Control) Legs of Subjects Without Known Cardiovascular or Neuromuscular Pathology[a]

| | Baseline[b] | Recovery 1[c] | Recovery 2[d] |
|---|---|---|---|
| **ST (n=20)** | | | |
| Calf blood flow (mL/100 mL/min) | | | |
| Left leg | 2.4±0.9 | 2.3±0.9 | 2.2±0.9 |
| Right leg | 2.2±0.9 | 2.2±1.3 | 2.0±0.9 |
| Calf vascular resistance (mm Hg/mL/100 mL/min) | | | |
| Left leg | 37.7±14.7 | 38.7±17.4 | 39.2±13.8 |
| Right leg | 44.9±21.4 | 42.5±19.2 | 47.6±21.4 |
| **MT (n=20)** | | | |
| Calf blood flow (mL/100 mL/min) | | | |
| Left leg | 2.5±0.9 | 2.4±0.9 | 2.3±0.9 |
| Right leg | 2.3±0.9 | 2.3±1.3 | 1.9±0.4 |
| Calf vascular resistance (mm Hg/mL/100 mL/min) | | | |
| Left leg | 36.1±13.8 | 40.5±20.1 | 38.7±17.0 |
| Right leg | 41.0±16.5 | 42.9±19.6 | 46.0±14.7 |
| **125% MT (n=20)** | | | |
| Calf blood flow (mL/100 mL/min) | | | |
| Left leg | 2.4±0.9 | 2.7±0.9 | 2.3±0.9 |
| Right leg | 2.1±0.9 | 2.0±0.9 | 1.8±0.9 |
| Calf vascular resistance (mm Hg/mL/100 mL/min) | | | |
| Left leg | 39.2±15.6 | 35.0±14.7 | 39.6±17.0 |
| Right leg | 47.9±24.5 | 48.1±21.4 | 49.9±17.0 |

[a] Values shown are mean±SD.
[b] Last 30 seconds of baseline period.
[c] First 30 seconds of recovery period.
[d] Second 30 seconds of recovery period.

cessation of stimulation (Tab. 1, Figs. 1 and 2). In contrast, TENS applied at intensities equal to, or just below, the motor threshold did not affect calf blood flow or vascular resistance (Tab. 1, Figs. 1 and 2). Mean arterial pressure was unaltered by TENS at any intensity level (Tab. 2). Likewise, dorsal and plantar foot temperature was unaltered by TENS at any intensity level (Tab. 2).

### *Static Handgrip Exercise*

As expected, 2 minutes of static handgrip exercise produced an increase in arterial pressure and vascular resistance in both legs from the baseline period to the final 30 seconds of the handgrip exercise (Tab. 3). Although vascular resistance in both legs increased 70% during the handgrip exercise, there was no concomitant change in dorsal or plantar skin temperature.

## Discussion

Several investigators[3–8] have hypothesized that transcutaneous stimulation of peripheral nerves, at various intensities and frequencies, can either increase or decrease activity in postganglionic vasoconstrictor neurons. However, the ability of transcutaneous stimulation to activate sympathetic vasoconstrictor fibers has not been demonstrated. For this reason, we investigated the effects of 3 different intensity levels of burst-mode TENS on calf blood flow, vascular resistance, and skin temperature. We chose burst-mode stimulation in order to mimic the naturally occurring, burst-like pattern of action potentials in sympathetic nerves.[10] We reasoned that vasoconstriction would be more likely to occur with burst-mode than with constant-frequency TENS because arterial smooth muscle is more responsive to irregular, low-frequency bursts of stimulation.[11,12] Our major finding is that burst-mode TENS produced vasodilation in the leg; however, this effect depended on stimulation intensity. When TENS was applied at or below the motor threshold, circulation was not affected. In contrast, when TENS was applied at an intensity 25% above the motor threshold, there was a transient vasodilation that lasted less than 1 minute. Regardless of stimulation intensity, TENS had no effect on skin temperature.

A frequently recommended electrode placement for the clinical use of TENS is directly over the peripheral nerve that serves the painful area.[13] Investigators who observed decreases in skin temperature during motor threshold TENS have raised the concern that TENS may decrease blood flow to a painful extremity by direct stimulation of

**Table 2.**
Mean Arterial Pressure (MAP) and Thermal Responses to Submotor Threshold (ST), Motor Threshold (MT), and 25% Above Motor Threshold (125% MT) Transcutaneous Electrical Nerve Stimulation (TENS) in the Left (Stimulated) and Right (Control) Legs of Subjects Without Known Cardiovascular or Neuromuscular Pathology[a]

| | Baseline[b] | Stimulation[c] | Recovery[d] |
|---|---|---|---|
| **ST (n=20)** | | | |
| Dorsal foot temperature (°C) | | | |
| Left leg | 29.4±2.2 | 29.6±2.2 | 29.5±2.2 |
| Right leg | 29.5±2.2 | 29.4±2.2 | 29.4±2.2 |
| Plantar foot temperature (°C) | | | |
| Left leg | 28.7±2.2 | 28.6±2.2 | 28.6±2.2 |
| Right leg | 28.9±2.6 | 28.9±1.7 | 28.9±2.6 |
| MAP (mm Hg) | 79±9 | 79±9 | 80±9 |
| **MT (n=20)** | | | |
| Dorsal foot temperature (°C) | | | |
| Left leg | 30.3±2.6 | 29.9±2.6 | 29.9±2.6 |
| Right leg | 29.7±2.6 | 29.0±3.1 | 28.5±3.1 |
| Plantar foot temperature (°C) | | | |
| Left leg | 29.3±2.6 | 28.8±2.2 | 28.9±3.1 |
| Right leg | 29.3±3.1 | 29.0±3.5 | 29.2±3.5 |
| MAP (mm Hg) | 79±9 | 78±4 | 79±9 |
| **125% MT (n=20)** | | | |
| Dorsal foot temperature (°C) | | | |
| Left leg | 29.8±2.2 | 29.8±2.2 | 29.7±2.2 |
| Right leg | 30.5±1.7 | 30.4±1.7 | 30.3±1.7 |
| Plantar foot temperature (°C) | | | |
| Left leg | 29.3±2.2 | 29.2±2.2 | 29.2±2.2 |
| Right leg | 29.7±1.7 | 29.5±1.7 | 29.7±1.7 |
| MAP (mm Hg) | 80±4 | 79±9 | 79±9 |

[a] Values shown are mean±SD.
[b] Final minute of baseline period.
[c] Final minute of stimulation.
[d] First minute of recovery period.

sympathetic vasoconstrictor fibers.[5] Our results suggest otherwise. Although we did not measure sympathetic outflow, we calculated vascular resistance, a variable that provides a more direct estimate of sympathetically mediated vasoconstriction than does skin temperature. Calf vascular resistance was not altered by burst-mode TENS applied at or slightly below motor threshold. Application of TENS at 25% above the motor threshold caused vasodilation, not vasoconstriction.

### *Hemodynamic Responses to Burst-Mode TENS*

Our findings of vasodilation in response to electrical stimulation that was 25% above motor threshold are consistent with previous reports that TENS increases local blood flow when the stimulation intensity is well above the motor threshold.[21,22] Because we did not observe systemic cardiovascular responses to any of the 3 stimulation intensity levels, we assume that the reductions in vascular resistance produced in the TENS trial that was 25% above motor threshold were caused mainly by local mechanisms. The "muscle pump,"[23,24] accumulation of local metabolic vasodilator substances,[25,26] and flow-induced vasodilation produced by local release of relaxing factors derived from the endothelium are potential mechanisms for the observed vasodilation.[27,28]

### *Skin Temperature Responses to Burst-Mode TENS*

Even though we provided at least 1 hour for acclimatization to the laboratory (24°±1°C) prior to data collection, we observed no effects of burst-mode TENS on skin temperature. Our findings differ from those of other investigators who reported decreases[5] or increases[6] in skin temperature after low-frequency TENS. Following 30 to 45 minutes of TENS applied at intensities high enough to elicit visible muscle contractions in patients with diabetic polyneuropathy or Raynaud phenomenon, Kaada[6] reported a rise in skin temperature of 7° to 10°C. One of the author's proposed explanations for the observed increase in skin temperature was a neurohumoral mechanism, because the post-stimulation temperature rise persisted for periods of 4 to 8 hours.[6] We think that this prolonged time course is incompatible with a pure neural event.

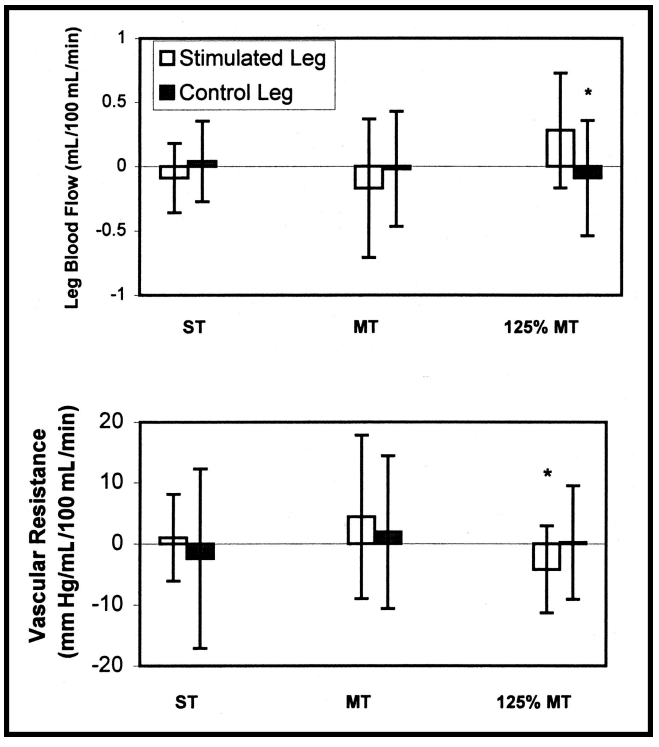


**Figure 1.**
Bar graphs depicting the group mean values for the change in leg blood flow (upper panel) and vascular resistance (lower panel) from baseline to immediately after stimulation between the stimulated leg (open bars) and control leg (closed bars). All 3 stimulation intensities of transcutaneous electrical nerve stimulation (TENS) are depicted. ST=submotor threshold, MT=motor threshold, and 125% MT=25% above motor threshold. Values shown are mean ± standard deviation. *Paired *t* test, *df*=19, *P*<.05, stimulated leg versus control leg.

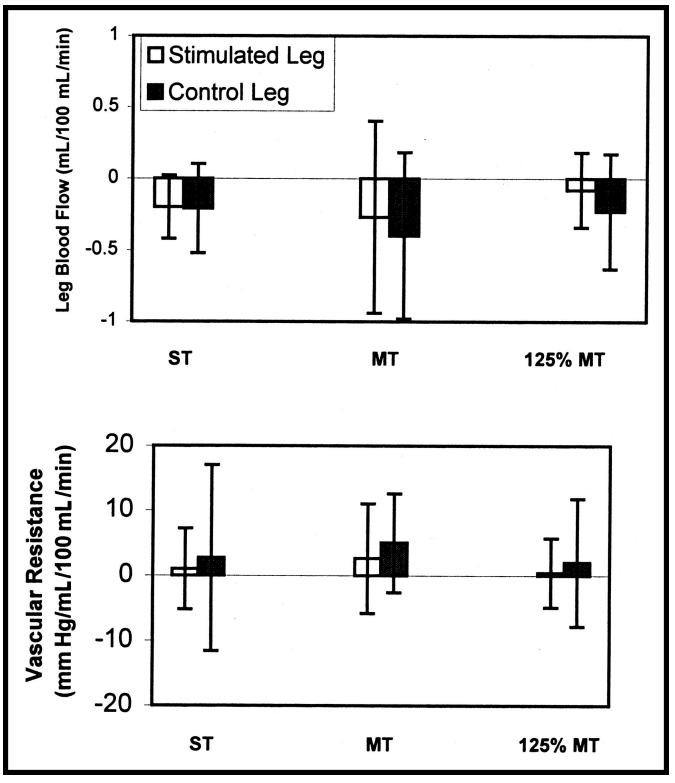


**Figure 2.**
Bar graph depicting the group mean values for the change in leg blood flow (upper panel) and vascular resistance (lower panel) from baseline to 30 seconds after stimulation between the stimulated leg (open bars) and control leg (closed bars). All 3 stimulation intensities of transcutaneous electrical nerve stimulation (TENS) are depicted. ST=submotor threshold, MT=motor threshold, and 125% MT=25% above motor threshold. Values shown are mean±standard deviation. Paired *t* test, *df*=19, *P*>.05, stimulated versus control leg.

We designed our study to assess the feasibility of transcutaneous stimulation of sympathetic fibers; therefore, stimulation was applied for only 5 minutes. Our results did not demonstrate any immediate hemodynamic effect from application of burst-mode TENS at or below the motor threshold. Our findings are inconsistent with those of Wong and Jette,[5] who reported that 25 minutes of motor threshold stimulation at high, low, and burst frequencies all caused a decrease in skin temperature of 2° to 3°C in humans who were healthy. These authors[5] proposed that the observed decrease in skin temperature was due to direct activation of vasoconstrictor nerves in the stimulated arm. However, the time constant for activation of sympathetic fibers[18,29,30] and for vasoconstriction following direct stimulation of sympathetic nerves is known to be less than 10 seconds.[31] Skin temperature was not continually monitored in the experiments of Wong and Jette[5]; therefore, the authors were unable to report on the time course for the effect on skin temperature.

Similar to Indergand and Morgan,[9] we also observed a small, progressive decrease in skin temperature over the 2- to 3-hour data collection period. There are 2 reasons why it is unlikely that this change was caused by electrical stimulation of sympathetic vasoconstrictor fibers. First, we did not notice any short-lived increases or decreases in temperature that coincided with the onset or cessation of the stimulation. Any measurable decrease in skin temperature was not apparent until after the commencement of the second trial, at least 25 minutes after the start of data collection. This decrease persisted throughout all subsequent trials. Second, and more importantly, comparable decreases were observed in the stimulated leg and the contralateral, unstimulated, leg. If we were directly stimulating sympathetic vasoconstrictor nerves, we would expect to see an effect only in the stimulated leg.

Although we chose to use clinically relevant stimulation parameters that we believe would mimic the naturally occurring burst-like pattern of sympathetic nerves, the intensity may not have been sufficient to elicit action potentials in sympathetic nerve fibers. Our failure to observe vasoconstrictive effects of TENS may be explained by the strength-duration curve for peripheral nerve fibers.[13,30] Postganglionic sympathetic fibers,

**Table 3.**
Hemodynamic and Thermal Responses to Static Handgrip Exercise (n=20) in the Left (Stimulated) and Right (Control) Legs of Subjects Without Known Cardiovascular or Neuromuscular Pathology[a]

| | Baseline[b] | Handgrip[c] | Recovery[d] |
|---|---|---|---|
| Calf blood flow (mL/100 mL/min) | | | |
| Left leg | 2.0±0.9 | 1.9±0.9 | 2.7±1.3 |
| Right leg | 1.8±0.9 | 2.0±0.9 | 2.5±0.9 |
| Mean arterial pressure (mm Hg) | 85±13 | 117±22 | 101±22 |
| Calf vascular resistance (mm Hg/mL/100 mL/min) | | | |
| Left leg | 49.8±19.7 | 75.4±42.0 | 48.3±31.3 |
| Right leg | 58.8±20.1 | 77.2±44.2 | 45.2±27.7 |
| Dorsal foot temperature (°C) | | | |
| Left leg | 29.0±2.2 | 29.0±2.2 | 29.0±2.2 |
| Right leg | 29.3±1.8 | 29.3±1.8 | 29.3±1.8 |
| Plantar foot temperature (°C) | | | |
| Left leg | 28.5±2.7 | 28.4±2.7 | 28.4±2.7 |
| Right leg | 28.7±4.0 | 28.7±4.0 | 28.6±4.0 |

[a] Values shown are mean±SD.
[b] Final 30 seconds of baseline period.
[c] Final 30 seconds of handgrip exercise.
[d] Final 30 seconds of recovery period.

because of their fiber diameter and conduction velocity, are C fibers.[29,30] In order to overcome the high external resistance of these thin fibers, stimulation intensities might have to be higher than those we used. These higher intensities probably would have elicited painful sensations; none of our subjects, however, told us that the stimulation was painful. Our findings do not support the possibility raised by other investigators[5] that transcutaneous electrical stimulation over peripheral nerves might have a vasoconstrictive effect. Our findings, as well as previous work from our laboratory,[9] both of which are based on more direct markers of sympathetic activity than skin temperature, lead us to question whether this is possible. Our data indicate that burst-mode electrical stimulation applied transcutaneously over peripheral nerves at clinically relevant pulse durations and frequencies does not cause vasoconstriction or cooling of the skin. In contrast, when the intensity of burst-mode TENS is increased to a level well above motor threshold, there is a transient vasodilatory effect, without any accompanying change in skin temperature.

### *Limitations*

The strain gauges used to register limb circumference during venous occlusion plethysmography are very sensitive to movement artifact; therefore, this technique cannot be used to measure blood flow during muscle contraction.[14,15] We took measurements immediately following the cessation of stimulation (within 1 second). We contend that these blood flow measurements closely approximate the undisturbed flow rate immediately prior to venous occlusion (ie, during muscle contraction).[14,15]

Venous occlusion plethysmography measures blood flow in the entire limb[15]; therefore, separate measurements of blood flow to muscle and skin cannot be obtained with this technique. We cannot determine, based on our data, whether the exercise-induced increases in blood flow occurred primarily in muscle, skin, or both vascular beds. We consider it unlikely, however, that changes in skin blood flow contributed to the observed changes in blood flow to a meaningful extent. The room temperature was maintained at a comfortable 24°C, and distractions inherent in the laboratory were kept to a minimum. Therefore, fluctuations in skin blood flow caused by thermoregulatory and arousal responses were minimized.[18]

In our experiments, there was intersubject variation in the level of force produced by the muscle contractions during the stimulation trial set at 25% above motor threshold. We do not believe that this failure to control the absolute level of force production diminishes the importance of our findings. Our intent was not to strictly control for motor output between subjects, but to approximate the intensity of muscle contractions that might be observed in clinical practice as well as provide a measurable means for reproduction of our experiment.

We considered the possibility that an inability to respond to vasoconstrictor stimuli was responsible for the negative findings in our subjects. Therefore, we assessed their responsiveness to 2 minutes of static handgrip exercise, an intervention that is known to cause time-dependent, sympathetically mediated vasoconstriction in the calf.[9,10]

In all subjects, we observed an increase in vascular resistance throughout the second minute of isometric exercise in both legs. Therefore, we believe it is unlikely that our negative findings can be attributed to a nonspecific failure of vasoconstrictor mechanisms.

## Conclusion

Our data are consistent with evidence obtained through direct stimulation of peripheral nerves: namely, that the activation threshold for sensory and motor fibers is below that of nociceptive C fibers.[30] We demonstrated that burst-mode TENS, applied at 3 different intensity levels that our subjects did not perceive as painful, does not cause vasoconstriction or cooling of the skin. Therefore, our data indicate that the belief that postganglionic sympathetic nerves can be stimulated transcutaneously in subjects with no known health problems using clinically relevant stimulation parameters is incorrect. We cannot exclude the possibility that, if TENS were of sufficient stimulation intensity to cause a painful response, it could stimulate sympathetic vasoconstrictor fibers. Future studies should investigate the immediate and long-term effects of burst-mode TENS on skin temperature, limb blood flow, and vascular resistance in subjects with known pathology.

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