The Influence of Sympathetic Nerves on Transcutaneous Oxygen Tension in Normal and Ischemic Lower Extremities

Thom W. Rooke, M.D.*
Larry H. Hollier, M.D.**
and
Philip J. Osmundson, M.D.*

ROCHESTER, MINNESOTA

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Abstract

The authors evaluated the relationship between sympathetic nerve activity and transcutaneous oxygen tension ($TcpO_2$) in normal and ischemic lower extremities. Dorsal foot $TcpO_2$ was measured by using oxygen-sensing electrodes with surface temperatures of 42°C and 45°C; in theory, changes in sympathetic activity should affect vasomotor tone and $TcpO_2$ in skin beneath an electrode at 42°C (submaximal vasodilation), but not at 45°C (maximal vasodilation). The vasodilation index ($TcpO_2$ at 42°C/$TcpO_2$ at 45°C) was created as an index of vasomotor tone (vasodilation index increases as tone decreases). In normal limbs (n=24) averages for $TcpO_2$ at 42°C, $TcpO_2$ at 45°C, and vasodilation index were 30.3 mmHg, 62.1 mmHg, and 0.47, respectively. In subjects (n=5) with quadriplegia and reduced sympathetic tone secondary to cervical cord trauma, $TcpO_2$ at 42°C and vasodilation index were increased (45.0 mmHg and 0.61); $TcpO_2$ at 45°C did not change. When normal subjects (n=7) were chilled for twenty minutes with a cooling blanket at 5°C (to increase sympathetic tone) average vasodilation index dropped from 0.50 to 0.29. Among ischemic limbs (n=34) vasodilation index was highly variable (range: 0-0.77); in general, vasodilation index fell as the ischemia worsened. In a subset of patients with ischemic limbs, the vasodilation index increased after the limb was wrapped in a warm dressing (average vasodilation index=0.25 without dressing, 0.37 with dressing). The authors conclude: (1) $TcpO_2$ can be used to assess the degree of vasomotor tone (and sympathetic activity) in skin; (2) tone generally increases as ischemia worsens; and (3) local warmth can improve cutaneous circulation in ischemic limbs.

From the Mayo Clinic and Mayo Foundation, *Division of Cardiovascular Diseases, **Head, Section of Vascular Surgery, Rochester, Minnesota

Introduction

Transcutaneous oxygen tension ($TcpO_2$) measurements are becoming increasingly useful in the noninvasive study of skin blood flow.[1-6] In theory, $TcpO_2$ depends upon a number of factors that can affect the diffusion of oxygen through skin, including the arterial pO_2 and the rate of cutaneous blood flow. When blood flow in skin is high, $TcpO_2$ approaches arterial pO_2; at low flow rates it primarily reflects the balance between cutaneous oxygen delivery and consumption.[7,8] It follows that in situations where blood flow is less than maximal, changes in perfusion will produce subsequent changes in $TcpO_2$. This principle underlies the use of $TcpO_2$ as an index of cutaneous blood flow.

Because skin temperature is an important determinant of cutaneous blood flow, most oximeters employ an oxygen-sensing (Clark-type) electrode that can be maintained at a constant, desired temperature. An electrode surface temperature of 43°-45°C usually provides sufficient heat to eliminate vasomotor tone and cause maximum vasodilation of the underlying skin.[3,9-11] In contrast, vasomotor tone may be present when lower electrode temperatures are used; under these conditions vasoactive stimuli will affect blood flow and $TcpO_2$.[12,13]

The fact that $TcpO_2$ measurements can be used to assess both maximum blood flow and vasoreactivity (depending upon the electrode temperature chosen) in skin makes this a potentially valuable tool for studying the effects of sympathetic nerves on cutaneous blood flow. The following describes a two-part preliminary study in which $TcpO_2$ measurements (taken at both higher and lower electrode temperatures) were used to evaluate the role of sympathetic nerves in the control of lower extremity skin blood flow. In the first part, the response of $TcpO_2$ to events known to change cutaneous sympathetic activity was determined in individuals with no evident circulatory disease. This information was used in the second part of the study to evaluate the influence of sympathetic activity on vasomotor tone and $TcpO_2$ in ischemic limbs.

Methods

Electrode Calibration

Transcutaneous oximeters were calibrated by using the two-point method recommended by the manufacturer. Daily adjustments were made as needed to accommodate changes in barometric pressure and room temperature. Accuracy was verified on several occasions by placing the electrode in a chamber containing a gas of known composition (10.1% oxygen with balance nitrogen and water vapor) and demonstrating that the measured and predicted pO_2's were equal. The relationship between real and measured pO_2 was linear for the three points studied (zero oxygen, 10.1% oxygen, and room air).

Dual Electrode Method

In some experiments, separate oximeters were calibrated and maintained at either 42°C or 45°C. The electrodes were attached to the dorsum of the foot (1-2 cm apart) and allowed to equilibrate (usually ten to twenty minutes). Although the sampling sites differed slightly between the electrodes, the $TcpO_2$ at 42°C and 45°C could be measured simultaneously by using the dual-electrode technique.

Single-Electrode Method

The calibration of the transcutaneous oximeter is affected by the temperature of the elec-

trode, and recalibration is normally required each time surface temperature is to be changed. It is, however, possible to correct for changes in pO_2 caused by differences in electrode temperature without recalibrating. For example, if an oximeter exposed to room air has been properly calibrated at 45°C to read 154 mmHg, a change in electrode temperature to 42°C will reduce the reading to approximately 140 mmHg. The true room air pO_2 can be calculated by multiplying 140 by a correction factor of 154/140 (or 1.1), yielding the corrected room air pO_2 of 154 mmHg. Similarly, for any measurement of $TcpO_2$ made with the electrode surface at 42°C (but with the oximeter previously calibrated at an electrode temperature of 45°C) the true $TcpO_2$ will exceed the measured value by a factor of 1.1. The appropriate correction factor can likewise be determined for any electrode temperature.

In certain experiments to be described the single-electrode technique was used to measure $TcpO_2$ at various temperatures without removing and recalibrating the electrode between each temperature change. Before attachment, the electrode was calibrated in room air at a surface temperature of 45°C; room air readings were subsequently determined at different temperatures as needed. These values were used to make the appropriate correction factors. After attachment, $TcpO_2$ measurements were made at the lowest temperatures first and then advanced to progressively higher temperatures. The $TcpO_2$ values obtained in this way (after correction for changes in electrode temperature) showed excellent agreement with measurements made using the dual-electrode method. In some studies, both the single- and dual-electrode methods were used, and the results were pooled.

Vasodilation Index

Cutaneous vasodilation (and a subsequent rise in $TcpO_2$) occurs as the electrode surface temperature is increased. In skin where vasomotor tone is low prior to the application of the electrode, the $TcpO_2$ should be relatively high even at low electrode temperatures, and little increase should be produced by additional heating. Conversely, in vasoconstricted skin the $TcpO_2$ at lower temperatures should be relatively low, and with heating the $TcpO_2$ should rise until the vasomotor tone in the region underlying the electrode reaches a minimum. To better compare and assess vasomotor tone, the vasodilation index (VI) was created. This index is defined as the $TcpO_2$ at a particular temperature divided by the $TcpO_2$ at 45°C.

$TcpO_2$ in Normal and Spinal-Cord-Damaged Subjects

Initial studies were performed on a single lower extremity from normal volunteers (no signs, symptoms, or history of circulatory disorder; n=8) and on otherwise healthy patients (n=7) admitted to the Saint Marys Hospital Rehabilitation Unit with total quadriplegia secondary to traumatic cervical spinal cord disruption (in 5 of these patients the interval since cord injury was six months or less). Measurements were usually made with the subject wearing a hospital gown; extremes in ambient temperature were avoided, but some room-to-room variation in temperature occurred. During the study the subject remained in the supine position and the limb was kept still. $TcpO_2$ electrodes were calibrated at 45°C prior to each use, coated with oxygen electrode contact gel, and attached to the dorsum of one of the subject's feet by means of rings of self-adhesive tape. Equilibration at 37°C was allowed to occur (defined as an oximeter reading that remained stable for at least sixty seconds; this typically required ten to twenty minutes). Temperature was then increased to 42°, 43°, 44°, and 45°C, with equilibration at each temperature occurring before the next increase was made. The electrode was

detached and calibration was rechecked; if the room air value at 45°C had changed by more than 5% from its prestudy value, the data were discarded and the measurements repeated. Measurements were corrected for temperature-induced changes in calibration as described for the single-electrode method.

In later studies it was decided to measure $TcpO_2$ at 42° and 45°C only, and the protocol for the single-electrode method was adjusted accordingly. These studies (n=16 for normals; n=4 for cord-damaged patients) were similar to those described above, except that the initial equilibration (usually requiring ten to fifteen minutes) was made at 42°C. Electrode temperature was then increased to 45°C until $TcpO_2$ equilibration was reestablished. $TcpO_2$ measurements were also made in 8 normal and 1 cord-damaged subject by using the dual-electrode method; the data were pooled with those obtained with the single-electrode method to form larger groups (n=24 for normals; n=5 for cord-damaged subjects).

$TcpO_2$ During Chilling

With normal subjects (n=7 limbs), two electrodes were attached to the dorsum of the foot and allowed to equilibrate for fifteen to twenty minutes, one at 42°C and the other at 45°C. Dorsal foot temperature was measured with a digital thermometer. After measurements of $TcpO_2$ were recorded, a cooling blanket at 5°C was placed over the trunk and thighs. Following fifteen to twenty minutes of chilling, the new values for dorsal foot temperature and $TcpO_2$ at 42° and 45°C were recorded.

Studies on Ischemic Lower Extremities

Dorsal foot $TcpO_2$ was determined in limbs (n=34) with known atherosclerotic peripheral vascular disease. Measurements were made by using both the single- (28 limbs from 22 subjects) and dual- (6 limbs from 6 subjects) electrode methods as described earlier.

Effects of Vascular Boots on $TcpO_2$

Physicians at the Mayo Clinic frequently protect and warm the ischemic lower extremities of hospitalized patients by wrapping the limb with a thick cotton pad from the knee down. The padding is covered and held in place by a cloth wrap. Circumferential ties are placed snugly around the leg and foot at several levels to secure the wrap. These protective and heat-conserving dressings are referred to as "vascular boots."[14] Hospitalized patients (n=13) upon whom vascular boots had been placed by their physicians were identified. These patients were either severely ischemic (with rest pain or ulcers) or had recently undergone arterial reconstructive surgery. Two dorsal foot electrodes (42° and 45°C) were attached and allowed to equilibrate for fifteen to twenty minutes. After the $TcpO_2$ was recorded, the boots were removed and left off for approximately twenty minutes. Dorsal foot temperature was also measured (at least 2-3 cm from any attached electrode) by using a digital thermometer. In some experiments the initial measurements were made without boots; the boots were subsequently put on for about twenty minutes and the measurements (with boots) were repeated.

Statistics

Data are expressed as the mean ± the standard error of the mean. Paired or unpaired t-tests were performed as indicated, and p values less than 0.05 were considered to be significant (two-tailed test). Unless otherwise specified, only significant values are discussed.

TABLE I

$TcpO_2$ versus electrode surface temperature at 42°C and 45°C in normal and spinal-cord-damaged subjects (modified protocol)

n (limbs/subjects)	Normal 24/22		Cord-Damaged 5/5	
	Mean	Range	Mean	Range
Age (years)	37.0±3.1	(17-72)	34.0±8.9	(17-77)
$TcpO_2$ at 42°C (mmHg)	30.3±2.2	(8-49)	*45.0±3.7	(36-56)
$TcpO_2$ at 45°C (mmHg)	62.1±2.1	(48-87)	73.2±5.5	(58-83)
Vasodilation index ($TcpO_2$ at 42°C/ $TcpO_2$ at 45°C)	0.47±0.03	(0.15-0.72)	* 0.61±0.03	(0.58-0.67)

*=different from normals, $p < 0.05$ (group t-test).

Results

$TcpO_2$ Versus Electrode Temperature in Normal Subjects and in Patients with Cervical Cord Disruption

Dorsal foot $TcpO_2$ was measured at temperatures between 37° and 45°C in 8 normal subjects (ages nineteen to forty-six years) by using the single-electrode method. Seven totally quadriplegic subjects (ages seventeen to sixty-six years) with documented cervical cord disruption were likewise examined. Although all quadriplegic patients had varying degrees of mild postural hypotension, none were currently requiring medication to support their blood pressure. By using the appropriate $TcpO_2$ values, the vasodilation index was calculated at each temperature for every subject. A comparison between the two groups revealed no difference in either $TcpO_2$ or vasodilation index at 37°, 43°, 44°, or 45°C. A significant difference in both $TcpO_2$ (33.3±3.2 mmHg in normal subjects vs 43.4±4.6 mmHg in cord-damaged subjects) and vasodilation index (0.51±0.04 in normal subjects vs 0.68±0.04 in cord-damaged subjects) did occur at 42°C.

Based upon this preliminary study the protocol was shortened so that $TcpO_2$ was determined at 42° and 45°C only. By using the shorter protocol, both normal (n=22 subjects, ages seventeen to seventy-two years) and cord-damaged (n=5 subjects, ages seventeen to seventy-seven years) individuals were examined (Table I). The previously noted differences in $TcpO_2$ and vasodilation index were again present ($TcpO_2$ at 42°C was 30.3 mmHg in normal subjects and 45.0 mmHg in cord-damaged subjects; vasodilation index was 0.47 and 0.61, respectively).

$TcpO_2$ and Cooling

Lower extremities from 7 normal subjects were examined before and after fifteen to twenty minutes of body cooling with a cooling blanket (5°C). During exposure to ambient room temperature the $TcpO_2$ (mmHg) at 42° and 45°C was 30.7 and 59.9, respectively (vasodilation index=0.50). Cooling decreased the $TcpO_2$ to 17.0 at 42°C and 58.0 at 45°C (vasodilation index=0.29). Dorsal foot temperature fell from 31.2° to 30.8°C with body cooling (Table II).

TABLE II
Effect of body chilling on $TcpO_2$

n=7 age (years)=30.0±5.3 (16-58)	Without Cooling Blanket	With Cooling Blanket
Dorsal foot temperature (°C)	31.2±0.04	*30.8±0.04
$TcpO_2$ at 42°C (mmHg)	30.7±4.9	**17.0±4.3
$TcpO_2$ at 45°C (mmHg)	59.5±2.8	58.0±3.9
Vasodilation index ($TcpO_2$ at 42°C/$TcpO_2$ at 45°C)	0.50±0.06	**0.29±0.07

*=different from control ($p < 0.05$) (paired t-test).
**=different from control ($p < 0.01$) (paired t-test).

TABLE III
$TcpO_2$ in ischemic limbs (n=34 limbs, 28 subjects)

	Claudication Only		Ulceration or Tissue Loss	
	Average	Range	Average	Range
N (limbs/subjects)	19/15		15/13	
Age (years)	68.9	(48-78)	67.8	(46.81)
SEM	±4.8		±4.7	
$TcpO_2$ at 42°C (mmHg)	18.5	(1-51)	*9.4	(0-42)
SEM	±2.7		±2.7	
$TcpO_2$ at 45°C (mmHg)	45.1	(16-65)	**33.1	(14-65)
SEM	±4.2		±3.7	
Vasodilation index	0.37	(0.03-0.82)	*0.23	(0-0.65)
SEM	±0.05		±0.04	

SEM=standard error of the mean.
*=different from value for claudication only ($p < 0.05$) (group t-test).
**=different from value for claudication only ($p < 0.01$).

$TcpO_2$ in Limbs with Vascular Disease

Dorsal foot $TcpO_2$ was measured in 34 ischemic limbs from 28 patients with atherosclerotic peripheral vascular disease. As a group, the mean $TcpO_2$ was 14.5 mmHg at 42°C and 40.8 mmHg at 45°C; the vasodilation index was 0.31. Because of the extreme variation in the severity of ischemia within this group ($TcpO_2$'s at 45°C ranged from 14 mmHg to 65 mmHg), the patients were divided into those with claudication (19 limbs from 15 patients) and those with ulcerations or tissue loss (15 limbs from 13 patients). All patients with claudication had either angiographic confirmation of severe disease or an ankle-brachial index of less than 0.60.

The vasodilation indices were calculated for each group. The index was 0.37 in those with claudication and fell to 0.23 in those with tissue damage (Table III).

Effect of Warming with Vascular Boots on $TcpO_2$

Dorsal foot $TcpO_2$ (dual-electrode method at 42° and 45°C) was determined in a group of patients upon whom vascular boots had been placed for the warmth and protection of their ischemic limbs. Indications for vascular boots included severe ischemia (n=8) or recent aortic surgery (n=5). Results are shown in Table IV. The application of vascular boots increased

TABLE IV
Effect of local warming on the $TcpO_2$ of ischemic lower extremities (n=13 limbs, 12 subjects) age (years)=61.2±4.5

	Without Vascular Boots	With Vascular Boots
Dorsal foot temperature (°C)	30.4±0.05	*31.8±0.05
$TcpO_2$ at 42°C (mmHg)	12.5±2.5	*17.8±3.5
$TcpO_2$ at 45°C (mmHg)	44.8±6.9	45.3±7.0
Vasodilation index	0.24±0.04	**0.37±0.06

*=different from control ($p < 0.01$) (paired t-test).
**=different from control ($p < 0.05$).

dorsal foot temperature by 1.4°C; no change in $TcpO_2$ at 45°C occurred as a result of this, but $TcpO_2$ at 42°C increased by 5.3 mmHg. The vasodilation index increased from 0.25 to 0.37.

Discussion

Sympathetic nerves are clearly important in the control of cutaneous blood flow.[15,16] Changes in body temperature appear to be one of the main physiological factors determining sympathetic vasomotor tone in the skin; ie, as temperature falls, there is an increase in sympathetic tone, resulting in cutaneous vasoconstriction and decreased heat loss. Several mechanisms are responsible for this effect, including an increase in the release of norepinephrine from sympathetic nerve endings[16] and a cold-induced increase in the affinity of vascular smooth muscle alpha-receptors for norepinephrine.[17,18] In certain situations (such as in response to extreme cold or in Raynaud's phenomenon) cold-induced cutaneous vasoconstriction may be so severe that ischemia results.

Measuring the influence of sympathetic nerve activity on cutaneous blood flow has always been difficult, and the techniques available to do this are limited. However, the observation that $TcpO_2$ is affected by various stimuli that alter vascular reactivity[12,13,19] suggested that changes in sympathetic tone might be reflected as changes in $TcpO_2$. If so, transcutaneous oxygen measurements could prove useful in studying the influence of sympathetic nerves on skin blood flow. The present study (limited to the lower limbs) was undertaken to evaluate this possibility. The goals were twofold: (1) to determine whether changes in sympathetic tone affected dorsal foot $TcpO_2$ in normal individuals and (2) if so, to determine whether $TcpO_2$ measurements can be used to evaluate the influence of sympathetic nerves on vasomotor tone and cutaneous blood flow in limbs affected by vascular occlusive disease.

The dorsum of the foot has proven to be a practical and somewhat standard site for studying limb $TcpO_2$.[2,4-6,10] In our first series, dorsal foot $TcpO_2$ was determined at a variety of electrode surface temperatures. As anticipated, heat produced vasodilation in the skin beneath the electrode, which resulted in a higher cutaneous blood flow (and therefore higher $TcpO_2$) as the electrode temperature rose. In keeping with the practice of others[9,10] we assumed that an electrode surface temperature of 45°C produced maximal vasodilation in the underlying skin, although this could not be confirmed with the equipment used in this study because 45°C was the highest available temperature setting. At lower electrode temperatures, vasomotor tone (and the ability of cutaneous blood vessels to respond to vasoactive stimuli) was partially maintained. The vasodilation index ($TcpO_2$ at a given temperature divided by $TcpO_2$ at 45°C)

was created as an index of vasomotor tone. Subjects with high tone (reflecting vasoconstriction) should have a low index, while those with lower tone should have a higher index.

The observed relationship between $TcpO_2$ and electrode surface temperature suggested that some degree of vascular tone was normally present in the skin of most supine individuals at room temperature. If sympathetic nerves contributed to the production of this tone, then the elimination of their influence should increase blood flow and $TcpO_2$ (for any given electrode temperature). As a first test of this hypothesis, the relationship between $TcpO_2$ and electrode temperature was evaluated in otherwise normal subjects with complete cervical cord disruption. Because of their injuries, it was anticipated that sympathetic innervation to the lower extremities would be reduced. We observed that $TcpO_2$ at 45°C was similar to that in normal subjects; however, at all other temperatures the trend was toward higher $TcpO_2$'s in the cord-damaged group. This difference was significant at 42°C. On the basis of these findings it was decided to adopt a shorter protocol in which dorsal foot $TcpO_2$ was measured at 42°C and 45°C only. The values obtained by use of this protocol agreed well with the previously obtained values for both normal and cord-damaged subjects.

The hypothesis that blood flow (and $TcpO_2$) at 42°C is affected by changes in sympathetic tone was further tested by taking normal subjects and covering them with a cooling blanket. The predicted response to this challenge would be an increase in cutaneous sympathetic tone and a subsequent decrease in skin blood flow. As expected, $TcpO_2$ at 42°C dropped markedly in response to chilling, while $TcpO_2$ at 45°C showed no significant change. The vasodilation index likewise declined with chilling.

These data suggest that changes in $TcpO_2$ at 42°C parallel the predicted vasomotor responses to decreased (cord-damaged) or increased (chilling) sympathetic nerve activity. Expression of the results as a vasodilation index helped to correct for patient-to-patient variation in several factors, including arterial oxygen content and blood pressure (this same reasoning has led to the use by others of the regional perfusion index for the assessment of limb blood flow[2]). The vasodilation index varied considerably among members of the normal group. Factors that might have contributed to the variability include: inherent neurological differences between individuals; environmental factors, such as room temperature, the amount of clothing worn by the subject during the study, etc.; drug effects (although none of these subjects admitted to taking antihypertensive medications or other drugs known to exert a primary effect on vascular tone, the possibility that unrecognized substances, such as aspirin, oral contraceptives, nicotine, caffeine, alcohol, over-the-counter cold remedies, or other medications, may have affected vasomotor tone exists); and nonspecific constitutional factors, including stress, exercise conditioning, or seasonal acclimatization.

The final series of studies were performed on patients with atherosclerotic peripheral vascular disease. The group was divided into those with either claudication or ischemic ulceration. As was the case with normal subjects the vasodilation index varied widely, but in general it decreased as the ischemia worsened. This phenomenon may have been due to the fall in limb skin surface temperature that typically accompanies occlusive disease.[20] Although surface skin temperature was not measured in this group of patients, it seems likely that the temperature was lower in patients with more severe occlusive disease. The lower skin temperature would, among other things, increase cutaneous blood vessel sensitivity to norepinephrine and thus

augment sympathetic tone. Support for this possibility was found by studying a select group of subjects upon whose limbs vascular boots had been placed to provide temporary warmth and protection. These dressings increased average skin temperature from 30.4° to 31.8°C and produced a subsequent increase in both $TcpO_2$ and vasodilation index at 42°C, without changing $TcpO_2$ at 45°C.

Our findings support the possibility that sympathetic activity and vasomotor tone may be increased in the skin of patients with occlusive vascular disease, paticularly as the ischemia becomes more severe. It is possible that the resulting vasoconstriction may further compromise an already insufficient cutaneous circulation; if so, the elimination of this tone might decrease cutaneous vascular resistance and improve blood flow. Keeping the ischemic limb warm may therefore be a practical way to attenuate sympathetic tone and improve local cutaneous blood flow and $TcpO_2$.

Many questions remain unanswered regarding the relationship between sympathetic activity and cutaneous blood flow, especially in the setting of ischemia. For example, how is blood flow in ischemic limbs affected by lumbar sympathectomy? Although surgical sympathectomy antedates vascular reconstruction as a method of improving cutaneous perfusion, it remains uncertain to what extent the increase in blood flow produced by this operation favorably influences the clinical outcome. Advocates of the procedure have provided considerable anecdotal evidence to support the use of lumbar sympathectomy in selected situations,[21-25] but no controlled study has ever demonstrated this operation to be an effective treatment for cutaneous ischemia caused by atherosclerosis (either as an isolated procedure or as an adjunct to revascularization). Some authorities have even argued that sympathectomy can cause "steal"[26] or that it increases arteriovenous shunting as opposed to nutritional flow.[27,28] Although we did not address these questions directly, our findings showed that changes in sympathetic activity caused subsequent changes in $TcpO_2$, which indicates that sympathetic nerves must influence nutritional blood flow. While it remains possible that cutaneous arteriovenous shunting is also affected by sympathetic activity, changes in shunting alone could not (by definition) have produced the changes in $TcpO_2$ observed in this study. Further work into the role of $TcpO_2$ measurements as a tool for the investigation of sympathetic nerve activity in ischemic limbs is clearly indicated.

Future studies may require more accurate and detailed assessments of $TcpO_2$. If so, several possibilities exist for improving upon the measurement process used in these studies. These include: (1) better control of variables, such as room temperature, skin exposure, and duration of electrode equilibration; (2) use of multiple sites for determination of $TcpO_2$ (blood flow in some sites might behave differently from blood flow in nearby regions); (3) optimizing the electrode surface temperatures for each subject (eg, 42°C may produce too much cutaneous vasodilation to detect vasomotor changes in one patient and too little vasodilation in another); (4) use of various maneuvers (such as standing or limb elevation) that may augment or attenuate blood flow; and, (5) determination of $TcpO_2$ on more than one occasion.

In summary, when measured at an electrode surface temperature of 42°C, dorsal foot $TcpO_2$ changes in response to events known to influence sympathetic tone. The vasodilation index (in this case, $TcpO_2$ at 42°C divided by $TcpO_2$ at 45°C) theoretically provides an indicator of cutaneous vasomotor tone. In normal subjects this index is increased by disruption of the

cervical spinal cord (reduced sympathetic nerve activity) and decreased by body chilling (increased sympathetic nerve activity). In ischemic limbs the vasodilation index decreases as the ischemia worsens; this may be due to a drop in skin temperature, but other factors cannot be ruled out. The $TcpO_2$ and vasodilation index in these patients can be improved by keeping the ischemic limb warm, but additional studies will be required to determine whether this improves the clinical outcome.

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Thom W. Rooke, M.D.
Division of Cardiovascular Diseases
Mayo Clinic
200 First Street, S.W.
Rochester, Minnesota 55905

References

1. Clyne CAC, Ryan J, Webster JHH, Chant ADB: Oxygen tension on the skin of ischemic legs. Am J Surg 143:315-318, 1982.
2. Hauser CJ, Shoemaker WC: Use of a transcutaneous pO_2 regional perfusion index to quantify tissue perfusion in peripheral vascular disease. Ann Surg 197:337-343, 1983.
3. Dowd GSE, Linge K, Bentley G: The effect of age and sex of normal volunteers upon the transcutaneous oxygen tension in the lower limb. Clin Phys Physiol Meas 4:65-68, 1983.
4. Wyss CR, Matsen FA, Simmons CW, Burgess EM: Transcutaneous oxygen tension measurements on limbs of diabetic and nondiabetic patients with peripheral vascular disease. Surgery 95:339-346, 1984.
5. Hauser CJ, Kline SR, Mehringer CM, et al: Superiority of transcutaneous oximetry in noninvasive vascular diagnosis in patients with diabetes. Arch Surg 119:690-694,1984.
6. Byrne P, Provan J, Ameli FM, Jones DP: The use of transcutaneous oxygen tension measurements in the diagnosis of peripheral vascular insufficiency. Ann Surg 200:159-165, 1984.
7. White RA, Nolan L, Harley D, et al: Noninvasive evaluation of peripheral vascular disease using transcutaneous oxygen tension. Am J Surg 144:68-75, 1982.
8. Transcutaneous oxygen measurement in skin ischaemia (editorial). Lancet 2(8398):329, 1984.
9. Ryan TJ: Dermal vasculature. In: Methods in Skin Research, ed. by Skerrow D and Skerro CJ. London, John Wiley & Sons, Ltd., 1985, pp. 527-558.
10. Dowd GSE, Linge K, Bentley G: Measurement of transcutaneous oxygen pressure in normal and ischaemic skin. J Bone Joint Surg 65:79-83, 1983.
11. Katsamouris A, Brewster DC, Megerman J, et al: Transcutaneous oxygen tension in selection of amputation level. Am J Surg 147:510-517, 1984.
12. Ewald U, Rooth G, Tuvemo T: Postischaemic hyperaemia studied with a transcutaneous oxygen electrode used at 33°-27°C. Scand J Clin Lab Invest 41:641-645, 1981.
13. Severinghaus JW, Stafford M, Thunstrom AM: Estimation of skin metabolism and blood flow with $TcpO_2$ and $TcpO_2$ electrodes by cuff occlusion of the circulation. Acta Anaesth Scand 68:9-15, 1978.
14. Fairbairn JF, Joyce JW, Pairolero PC: Acute arterial occlusion of the extremities. In: Peripheral Vascular Diseases, ed. by Juergens JL, Spittell JA, Fairbairn JF. Philadelphia, W.B. Saunders Co., 1980, pp. 391-392.
15. Clement DL: Sympathetic nervous control of muscle and skin circulation. J Cardiovasc Surg 20:291-342, 1979.
16. Rowell LB: Reflex control of the cutaneous vasculature. J Invest Dermatol 69:154-166, 1977.
17. Shepherd JT, Vanhoutte PM: The Human Cardiovascular System. New York, Raven Press, 1979, pp. 91-106.
18. Vanhoutte PM, Cooke JP, Lindblad L-E, et al: Modulation of postjunctional α-adrenergic responsiveness by local changes in temperature. Clin Sci 68:121s-123s, 1985.
19. Kram HB, Appel PL, White RA, Shoemaker WC: Assessment of peripheral vascular disease by postocclusive transcutaneous oxygen recovery time. J Vasc Surg 1:628-634, 1984.
20. Juergens JL, Bernatz PE: Atherosclerosis of the extremities. In: Peripheral Vascular Diseases, ed. by Juergens JL, Souttell JA, Fairbaird JF. Philadelphia, W.B. Saunders Co., 1980, pp. 261-293.
21. Imparato AM: Lumbar sympathectomy: Role in the treatment of occlusive arterial disease in the lower extremities. Surg Clin North Am 59:719-736, 1979.
22. Blain A, Zadeh AT, Teves ML, Bing RJ: Lumbar sympathectomy for arteriosclerosis obliterans. Surgery 53:164-170, 1963.
23. Szilagyi DE, Smith RF, Seerpella JR, Hoffman K: Lumbar sympathectomy: Current role in the treatment of arteriosclerotic occlusive disease. Arch Surg 95:753-761, 1967.
24. Frymark WB, Sullivan JM: Lumbar sympathectomy for arteriosclerotic peripheral vascular disease. Ann Surg 138:759-764, 1953.

25. Moore WS, Hall AD: Effects of lumbar sympathectomy on skin capillary blood flow in arterial occlusive disease. J Surg Research 14:151-157, 1973.
26. Carey JP, Stemmer EA, Heber RE, Connolly JE: The effectiveness of bilateral sympathectomy for unilateral occlusive arterial disease. Am Surg 33:772-778, 1967.
27. Cronenwett JL, Lindenauer SM: Direct measurement of arteriovenous anastomotic blood flow after lumbar sympathectomy. Surgery 82:82-89, 1977.
28. Freeman NE, Leeds JH, Gardner RE: Sympathectomy for obliterative arterial disease: Indications and contraindications. Ann Surg 126:873-894, 1947.