Assessment of the Characteristics and Detectability of Skin Perfusion Pressure Measured Using a Thermostatic Heating Probe

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Objectives: To assess the characteristics of skin perfusion pressure (SPP) measured using a thermostatic heating probe and whether a thermostatic heating probe improves SPP detection.

Methods: We studied 8 feet of healthy young subjects and 31 feet of elderly patients suspected to have severe limb ischemia. We measured SPP at the dorsum and plantar aspects of each foot using a plain laser Doppler probe and a thermostatic heating probe heated at 44°C. Results were expressed as median. Comparisons were analyzed using a non-parametric test.

Results: In the healthy subjects, the SPP values at both the dorsum and the plantar aspect were not significantly different after heating. The thermostatic heating probe did not improve the SPP detection rates. In the patients with ischemic limb, the SPP values at both the dorsum and the plantar aspect significantly increased after heating (p <0.001 for both). The SPP detection rate at the dorsum remained at 96.8%; however, it was improved from 87.1% to 100% at the plantar aspect after heating.

Conclusion: The thermostatic heating probe was shown to be useful for improving the detectability of SPP in the ischemic limbs. An SPP increase after heating may be considered as a parameter of limb ischemia.

Keywords: skin perfusion pressure, skin temperature, thermostatic heating probe, response by heating, critical limb ischemia

INTRODUCTION

Skin perfusion pressure (SPP) measurement using a laser Doppler perfusion monitor is useful for evaluating limb ischemia. However, SPP is usually difficult to detect in limbs with severe ischemia. Skin perfusion is strongly dependent on temperature and environment. Among patients with limb ischemia, some have very poor skin perfusion as SPP can hardly be detected. On the other hand, there are also many patients whose low skin temperature makes SPP detection in their limbs even more difficult.

To measure SPP in an ideal condition, Castronuovo, et al. used a warm heating pad for 15 minutes to elevate the baseline skin perfusion to reach the detectable level by a laser Doppler monitor before the measurement.1) For SPP measurement, the examination room must be warm and the limbs must be properly warmed. However, even in an adequately warmed examination room, it remains troublesome and time-consuming to warm cold limbs, particularly for outpatients.

Skin perfusion is associated with surface temperature
SPP Measurement Using a Thermostatic Heating Probe

SPP using a plain probe at the dorsum and plantar aspects and then measured similarly using a thermostatic heating probe. When using the thermostatic heating probe, measurement was started after waiting for about 10–20 seconds until the baseline blood flow volume was stabilized. The pressure cuff was inflated to 100 mmHg manually and deflated automatically (3.4 mmHg/sec).

All statistical analyses were performed using JMP statistical software (version 9.0.2; SAS Institute, Cary, North Carolina, USA). Results were expressed as median (interquartile range). Comparison of age between the 2 groups was analyzed using the Wilcoxon rank-sum test, and other characteristics were compared using the Fisher exact test. The differences in SPP between the 2 types of probes and the differences in SPP between the 2 aspects of the foot were analyzed using the Wilcoxon signed-rank test. The effects of background diseases on SPP changes induced by heating of the feet of patients were analyzed using the Wilcoxon rank-sum test. A p-value of less than 0.05 was considered to indicate a statistically significant difference. When the SPP value was undetectable, it was treated as a missing value.

Results

The characteristics of the patients are summarized in Table 1. The patients were older than the healthy subjects and had a high proportion of hypertension.

We compared the values and detection rates of SPP, which changed according to the probes used (Figs. 1 and 2). In the healthy subjects, the SPP values at the dorsum and

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Table 1 Demographic characteristics and backgrounds of the subjects

<table>
<thead>
<tr>
<th>Group</th>
<th>Healthy subjects</th>
<th>Patients</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of feet</td>
<td>8</td>
<td>31</td>
<td>&gt;0.99</td>
</tr>
<tr>
<td>Male:Female</td>
<td>4:4</td>
<td>16:15</td>
<td>&gt;0.99</td>
</tr>
<tr>
<td>Age, median years (range)</td>
<td>21 (20–21)</td>
<td>85 (57–93)</td>
<td>&lt;0.001**</td>
</tr>
<tr>
<td>Ankle pressure (mmHg)*</td>
<td>54 (20–82)</td>
<td>0.34 (0.05–0.68)</td>
<td>&lt;0.001**</td>
</tr>
<tr>
<td>ABI*</td>
<td>0.0 (0–44)</td>
<td>0 (0–0.35)</td>
<td>&lt;0.001**</td>
</tr>
<tr>
<td>Toe pressure (mmHg)*</td>
<td>0</td>
<td>0</td>
<td>&gt;0.99</td>
</tr>
<tr>
<td>TBI*</td>
<td>0 (0–35)</td>
<td>0.0 (0–0.35)</td>
<td>&gt;0.99</td>
</tr>
<tr>
<td>Rest pain, n (%)</td>
<td>9</td>
<td>18 (58.1)</td>
<td>&gt;0.99</td>
</tr>
<tr>
<td>Ulcer, n (%)</td>
<td>9 (29.0)</td>
<td>0 (0)</td>
<td>&gt;0.99</td>
</tr>
<tr>
<td>Background disease, n (%)</td>
<td>0</td>
<td>0 (0)</td>
<td>&gt;0.99</td>
</tr>
</tbody>
</table>

*: median (interquartile range), **: Significant difference. ABI: ankle brachial pressure index; TBI: toe brachial pressure index.
plantar aspects showed no significant difference between the plain laser Doppler probe and the thermostatic heating probe ($p = 0.35$ and $p = 0.41$, respectively). At the dorsum, the SPP detection rates were equal (87.5%) because there was only 1 foot with undetectable SPP for each probe (Fig. 1A). The SPP detection rate at the plantar aspect was 100% when using the plain laser Doppler probe, but it decreased to 87.5% when using the thermostatic heating probe (Fig. 1B).

In the feet of the patients, both SPP values at the dorsum and plantar aspects of the feet increased significantly when the thermostatic heating probe was used (Fig. 2A and 2B; $p < 0.001$ for both). At the dorsum, there was 1 foot in which SPP was undetectable even when the thermostatic heating probe was used; the SPP detection rate was 96.8% using both probes (Fig. 2A). The SPP detection rate was 87.1% when the plain laser Doppler probe was used (number of feet with undetectable SPP = 4), but the rate reached 100% when a thermostatic heating probe was used (Fig. 2B).

There were 7 feet that showed an SPP of 30 mmHg or less at both aspects whichever probe was used, including 5 with ulcer. The 2 feet with ulcer belonged to 1 patient who had diabetes and renal disorder and who later died in the hospital. In her right foot, the SPP was undetectable at the dorsum whichever probe was used. There were 4 feet in which SPP became detectable using the thermostatic heating probe. Of these, 3 feet were the remaining feet with ulcer that showed an SPP of 30 mmHg or less in both aspects whichever probe was used; 1 of these needed major amputation. The remaining 1 foot, in which SPP became detectable as 34 mmHg after heating, did not have ulcer. There were 6 feet that showed an SPP of 50 mmHg or more at both aspects when the thermostatic heating probe was used; these feet did not have ulcer. Although three of them were observed, no patient developed ulcer during their hospitalization. There were no statistically significant effects of comorbidities on SPP increase.

Figure 3 shows the comparisons of the SPP values between the aspects of the feet of the healthy subjects.
measured using the plain laser Doppler probe and thermostatic heating probe. Figure 4 shows the same comparisons of the patients. Regardless of the probes used, the SPP values were not significantly different between the dorsum and plantar aspects in each group.

**DISCUSSION**

SPP measurement is affected by skin temperature. SPP is difficult to measure in cold ischemic limbs and requires limbs to be warmed before measurement. Castronuovo, et al. used a warm heating pad for 15 minutes when baseline skin perfusion was less than 0.3 volume % units before the measurement. In contrast, the thermostatic heating probe can elevate and stabilize skin perfusion in about 1 minute, which is very helpful and advantageous in SPP measurement. Although there are currently no reports regarding SPP measurement using a thermostatic heating probe, we projected that the use of such probe would be convenient to improve SPP measurement in ischemic limbs.

We investigated the characteristics and detection rates of SPP measurement using a plain laser Doppler probe and a thermostatic heating probe in young healthy subjects and patients suspected to have severe limb ischemia. In the healthy subjects, the SPP values and the changes after heating varied, with 3 subjects showing an undetectable SPP in any 1 of 4 measurements. On the other hand, the detectability of SPP was improved at the plantar aspect of the feet in the patients when the thermostatic heating probe was used. The median SPP values increased in the feet of the patients after heating.

Skin perfusion is controlled by a sympathetic mechanism and a non-sympathetic local mechanism. Previous studies have shown that skin perfusion is increased by artificial heating, with a large increase in young people, but is decreased in elderly people. Nitric oxide (NO) production of the vascular endothelium is considered to be one of the non-sympathetic mechanisms of capillary dilation induced by heating; therefore, the response to heating is decreased in elderly people. On the other hand, Kingma, et al. reported that aging does not alter...
noradrenergic sensitivity during local cooling at the dor-
sal and ventral sides of the hand, and vasoconstriction by
a local mechanism was able to compensate in the hairless
skin area when a noradrenergic mechanism is blocked
even in elderly subjects.\textsuperscript{10} As the patients in this study
were elderly, sympathetic function might be reduced, and
they may also have ischemic damage resulting in auto-
sympathetic denervation in their feet, whereas they
might maintain local vasoconstriction function in
response to coldness. The thermostatic heating probe is
considered to induce a non-adrenergic local vasodilation
response. Even the ischemic feet of aged patients show
redness and warmth when infected. In addition, severe
ischemic feet had also shown an increase in skin perfu-
sion in warm water foot bath.\textsuperscript{11} Also in this study, some
ischemic feet in the elderly patients appeared to maintain
vasodilation responsiveness to temperature. There were
4 feet in which SPP became detectable using the ther-
mostatic heating probe. However, even though the SPP
became detectable, the states of the feet with ulcer in
which SPP could not reach 30 mmHg in both aspects
were worse as shown in previous reports on traditional
SPP measurement.\textsuperscript{12,13} On the other hand, the foot in
which the SPP became detectable as larger than 30 mmHg
did not have ulcer. Additionally, there were no feet that
developed ulcer in which the SPP values exceeded
50 mmHg in both aspects of the feet after heating. Thus,
the thermostatic heating probe may be useful for distin-
guishing feet with a poor SPP detection from feet with a
truly poor perfusion. An increase in SPP as induced by
local heating may serve as a parameter for evaluating the
severity of limb ischemia. However, the clinical mean
SPP measured using a thermostatic heating probe
remained unclear in this study and thus warrants further
investigation.

SPP detection is occasionally difficult even in non-
severe ischemic limbs. From the present results, difficul-
ties in SPP measurement may not be completely resolved
only with the use of a heating probe. The vasoconstrictor
and vasodilator responses of the skin according to tem-
perature are considered stronger in young people than
in elderly people.\textsuperscript{10,14} However, SPP measurement is
affected by not only temperature but also many factors
involving sympathetic nervous tension.\textsuperscript{15} The different
values in young healthy subjects may have resulted from
the strong sympathetic nerve tension offsetting the
response by heating. On the other hand, at the plantar
aspect, the feet that had shown a high SPP by the plain
laser Doppler probe appeared to have a small or no
increase in SPP after heating. The plantar aspect of the
healthy feet might be sufficiently warm or the SPP might
be sufficiently high when the plain probe was used. We
could not fully explain this because we did not measure
the skin temperature before the measurement using a
plain probe in both healthy and ischemic feet. However,
for the elderly patients with cold ischemic limbs, a ther-
mostatic heating probe could be useful in preparing the
skin temperature condition for measuring SPP in a
short warm-up time, as well as for improving the SPP
detection rate.

The SPP values measured using the plain laser Dop-
pler probe were statistically similar for both the dor-
sum and the plantar aspect of the feet in the healthy subjects.
However, as skin perfusion and response to temperature
are different in each body area, SPP also shows different
values by area.\textsuperscript{16–18} Previous studies have shown that
SPP tends to have higher values in the plantar aspect and
toe than in the dorsum.\textsuperscript{16,19} The skin plays a major role in
the thermoregulatory function in response to tempera-
ture, particularly in hairless skin areas such as the palms,
fingertips, plantar aspect of the feet, and toe tips, which
have more arteriovenous anastomosis than the other skin
areas.\textsuperscript{10,21} Masaki, et al. previously measured SPP at the
dorsum and toe in 20- to 23-year-old subjects. They
found that the SPP at the dorsum was 48 mmHg, which
is not significantly different from the SPP measured in
the current study (45 mmHg); the SPP at the toe was 64
mmHg, which is significantly higher than the SPP at the
dorsum.\textsuperscript{10} Castronuovo, et al. measured SPP at the calf,
foot, dorsal toe, and plantar toe in normal limbs and then
obtained the SPP value at the plantar toe (73 mmHg),
which was higher than the SPP value in all other loca-
tions.\textsuperscript{10} On the other hand, Fischer, et al. reported an SPP
of 81 mmHg at the dorsum among healthy persons.\textsuperscript{17}
Okamoto, et al. reported an SPP of 74 mmHg at the
dorsum in dialysis patients without peripheral arterial
disease and an SPP of 79 mmHg in healthy individu-
als.\textsuperscript{18} These SPP values at the dorsum are higher than
the SPP values of the healthy subjects in this study as
measured using a thermostatic heating probe. Although
the cause of the difference in the SPP values at the dor-
sum between the previous studies and this study was
unclear, age might have affected the results (our healthy
subjects showed lower SPP values also at the plantar
aspect [45 mmHg]); however, a description of the sub-
jects’ age in these previous studies was lacking.\textsuperscript{17,18} In
the patients in this study, the detectability of SPP was
improved at the plantar aspect but not at the dorsum.
Such phenomenon at the dorsum was observed in 1 foot suspected to have a truly poor perfusion. However, it is also possible that the difference in response after heating may reflect the distribution of arteriovenous anastomosis.

The results of SPP measurement can be affected by the measurement systems employed. We used PeriFlux System 5000 to measure SPP in this study. Previously, we compared the SPP values measured using Laserdopp Model PV2000 (Vasamedics Inc., USA) and PeriFlux System 5000 in young healthy subjects and PAD patients, and reported that PeriFlux System 5000 obtained a higher SPP value of 4–9 mmHg than Laserdopp Model PV2000. As for the difference between both systems, PeriFlux System 5000 reads values by 1 mmHg, whereas Laserdopp Model PV2000 reads values by 10 mmHg for values above 50 mmHg and by 5 mmHg for values less than 50 mmHg. This means that 79 mmHg as measured using PeriFlux System 5000 may be measured as 70 mmHg when using Laserdopp Model PV2000. Thus, the results may have a maximum difference of 9 mmHg for values larger than 50 mmHg, and may have a maximum difference of 4 mmHg for values smaller than 50 mmHg. Moreover, the measurement depth of the laser Doppler probe of PeriFlux System 5000 is 0.5–1.0 mm from the skin surface, which is slightly shallower than that of Laserdopp Model PV2000 (1–2 mm). This factor may affect the measurement.

CONCLUSION

In the healthy subjects of this study, the SPP values at the dorsum and plantar aspect of the feet showed no statistically significant difference between the plain laser Doppler probe and the thermostatic heating probe. In the patients with ischemic limb, the SPP values were increased and the detection rates were improved using the thermostatic heating probe. Thus, a thermostatic heating probe may be useful for preparing a temperature condition similar to the skin temperature in order to effectively measure SPP and improve its detection rate in ischemic feet. An increase in SPP as induced by heating may be used as a parameter for evaluating limb ischemia and the skin reserve capacity.

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DISCLOSURE STATEMENT

The authors declare that they have no conflicts of interest associated with this study.

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