Near-infrared spectroscopy of the thenar eminence: comparison of dynamic testing protocols

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ABSTRACT

Background: Near-infrared spectroscopy of the thenar eminence (NIRSth) is a non-invasive bedside method for assessing tissue oxygenation. The vascular occlusion test (VOT) with a pressure cuff can be used to provide a dynamic assessment of the tissue oxygenation response to ischaemia. VOT has been applied to assess the microcirculation by NIRSth in critically ill patients. The optimal mode of performing such VOT, however, remains controversial.

Design, participants and setting: Prospective observational study among a cohort of 11 healthy volunteers in a tertiary intensive care department.

Intervention: Measurement of NIRS-derived parameters using 1-, 2- and 3-minute VOTs or VOT to 40% tissue oxygen saturation (StO_2).

Main outcome measure: Changes in StO_2 and tissue haemoglobin index (THI) over time, and relative change from baseline for StO_2 and THI.

Results: Mean baseline StO_2 was 80% (SD, 5%) and mean THI was 13.7 (SD, 1.9). The lowest StO_2 at the end of the VOT was 39% (SD, 13%) and 39% (SD, 2%) in the 3-minute and the 40% StO_2 VOTs, respectively. The duration of the 40% StO_2 VOT ranged from 1:35 to 8:21 minutes (median, 3:29 min). There was a difference between the StO_2 curves for the 3-minute and 40% StO_2 VOT ($P = 0.005$) but not the THI curves. Reported pain score was a median of 3.5 (IQR, 2.5–5.5) and 4 (IQR 2–4) for the 3-minute and 40% StO_2 VOTs, respectively.

Conclusions: The 3-minute VOT and the 40% StO_2 appear equivalent. However, the 3-minute VOT carries a degree of decreased patient discomfort and shorter overall duration of execution.

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The microcirculation is the site of oxygen and nutrient exchange between the blood and the tissues.[1] Bedside monitoring of the microcirculation may, therefore, provide valuable information to the clinician. Near-infrared spectroscopy (NIRS) has been available for this purpose for some years.[2] This technology measures the tissue oxygen saturation (StO_2) of haemoglobin in small vessels within a few centimetres from the skin[3] and provides an estimate of the haemoglobin concentration in the same area. Since these "static" parameters can be influenced by local factors such as temperature and sympathetic tone,[4] dynamic values — changes in StO_2 during a vascular occlusion test (VOT) — have been proposed as a more useful method of investigating the microcirculation.[5]

Although several superficial tissues have been investigated with NIRS,[6,7] in recent years, NIRS of the thenar eminence (NIRSth) has attracted some attention. Although peripherally located, the thenar muscles are easily accessible and can be subjected to VOT.[8] The reaction of the thenar microcirculation to ischaemia reperfusion during VOT is measured during temporary occlusion of the brachial vessels. As NIRS of the thenar eminence could be part of standard bedside monitoring, technical and methodological issues regarding its use are now of importance. In particular, the intensity and/or duration of the VOT are a matter of controversy, with some authors advocating a 3-minute VOT,[9,10] and others advocating an occlusion to an StO_2 of 40%,[11,12] and no information on whether shorter occlusion times might still be acceptable.

Thus, we sought to investigate the quality of NIRSth measurements with dynamic tests of different duration by comparing VOTs of 1, 2 and 3 minutes and focusing on the 3-minute and 40% StO_2 VOT. Additionally, we investigated the duration of hyperaemia after VOT and, finally, we assessed reproducibility by comparing VOT in the right and left arms.

Methods

This study was approved by the Austin Hospital Human Research Ethics Committee (approval no. EER 04466).

We performed baseline NIRS measurements in a cohort of healthy volunteers and used the InSpectra StO_2 Spot Check model 300 NIRSth probe (Hutchinson Technology Inc, Hutchison, Minn, USA) with 15 mm spacing between light source and sensor. This NIRS device updates StO_2 and tissue haemoglobin index (THI) on the display every 2 seconds.

We placed the NIRS over the thenar eminence. If the level of signal was not maximal according to the NIRS monitor,

Table 1. Demographic and physiological data of volunteers participating in vascular occlusion tests

Characteristic	
Mean age in years (SD)	38 (9)
Mean body mass index, kg/m^2 (SD)	23 (3)
Asian, no. (%)	3 (33%)
Caucasian, no. (%)	6 (67%)
Male/female, no.	5/4
Mean heart rate, beats/min (SD)	67 (10)
Average mean arterial pressure, mmHg (SD)	85 (7)

we repositioned the probe until the best possible signal was achieved. We recorded baseline values after at least 1 minute of stabilisation and a variation of StO_2 of less than 2% over 10 seconds. For comparison of the StO_2 in the right and left thenar eminence, we completed measurements immediately after each other.

Vascular occlusion test

We performed the VOT by inflating a blood pressure cuff quickly to > 30 mmHg above the systolic blood pressure and releasing it according to the experimental protocol. We maintained vascular occlusion for 1, 2 or 3 minutes or until StO_2 40% was reached.

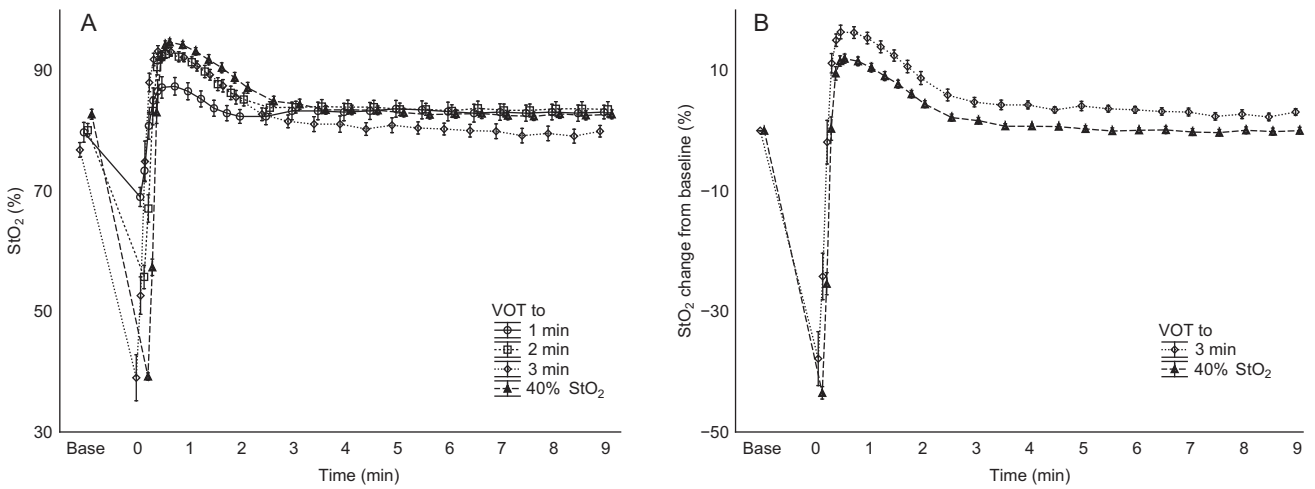
We used changes (delta) in StO_2 and THI over time, occlusion time during the VOT, amplitude of the ischaemia–reperfusion response (StO_2 max–min), rate of StO_2 decrease during vascular occlusion, rate of StO_2 increase (R_{res}), tissue oxygen consumption (tVO_2), hyperaemia after occlusion, and the level of pain during VOT as terms of comparison.

Delta StO_2 was calculated as the difference in StO_2 and baseline StO_2; delta THI was calculated in a corresponding way; occlusion time was measured by stopwatch; amplitude of the ischaemia–reperfusion response was defined as the difference between the highest and the lowest StO_2 during and after VOT; and the rate of StO_2 decrease during vascular occlusion was measured at the steepest part of the StO_2 curve. Conversely, R_{res} was measured at the steepest part of the StO_2 curve after the release of the vascular occlusion. Tissue oxygen consumption (tVO_2) was estimated by the product of StO_2 decrease and the mean THI during the same period during vascular occlusion. Hyperaemia after occlusion was characterised as the area of StO_2 above baseline over time. To assess pain, participants were informed about the numerical rating scale (NRS) pain scale[13] and asked about the level of discomfort during the VOT procedure.

To assess the effect of increasing occlusion time, we performed a 1-minute VOT on the right arm, a 2-minute VOT on the left arm and a 3-minute VOT on the right arm again. To assess reproducibility, the 40% StO_2 VOT was performed on both the right arm and on the left arm.

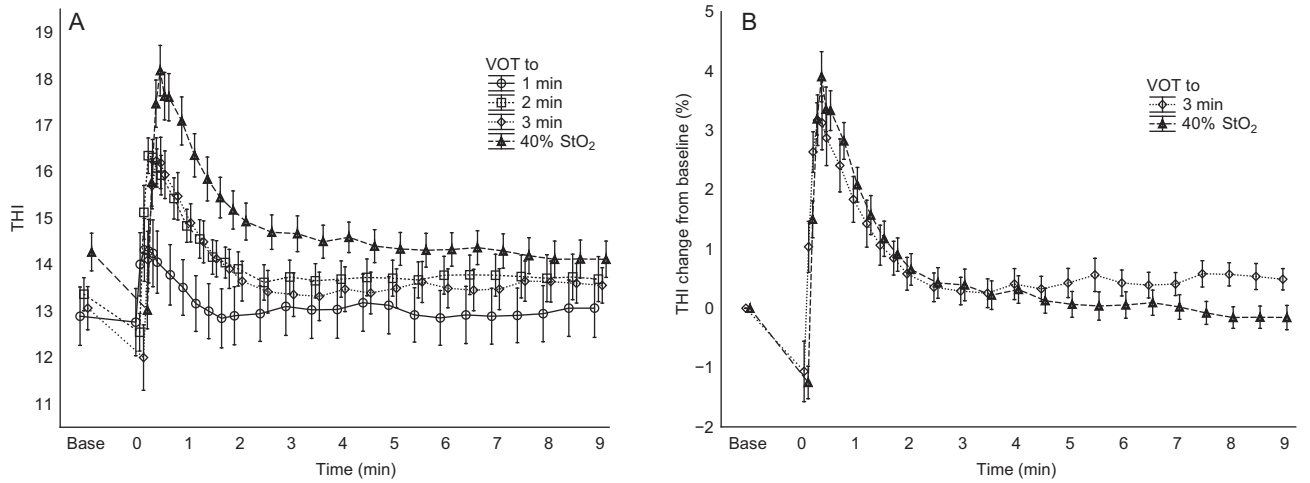
During vascular occlusion, StO_2 and THI were recorded every 15 seconds. After the release of the pressure cuff, values were recorded every 5 seconds to 30 seconds, and thereafter every 15 seconds until 9 minutes after the vascular occlusion. The 1-minute and 3-minute VOTs were, therefore, separated by > 10 minutes.

Figure 1. Mean tissue oxygen saturation (StO_2) and mean percentage StO_2 change from baseline for various vascular occlusion tests (VOTs)



Mean StO_2 (SE) for 1-, 2- and 3-minute and 40% StO_2 VOTs. **B.** *Mean percentage StO_2 change (delta) from baseline (SE) for 3-minute and 40% StO_2 VOTs.*

Figure 2. Mean tissue haemoglobin index (THI) and mean percentage THI change from baseline for various vascular occlusion tests (VOTs)



A. *Mean THI (SE) for 1-, 2- and 3-minute and 40% StO_2 VOTs.* B. *Mean percentage THI change (delta) from baseline (SE) for 3-minute and 40% StO_2 VOTs.*

Statistical analysis

Variables were tested for normality. Analysis of variance for repeated measurements was used to assess differences in StO_2 and THI over time during the experiment. We used the *t* test or Wilcoxon matched pairs test and Spearman rank correlations where appropriate. Bland–Altman plots were derived for comparing agreement between measurements.[14] Values are given as mean (SD) for variables with normal distribution and median (interquartile range [IQR]) for variables with non-normal distribution. $P < 0.05$ was considered statistically significant. STATISTICA, version 10 (StatSoft, Tulsa, Okla, USA) was used for statistical calculations.

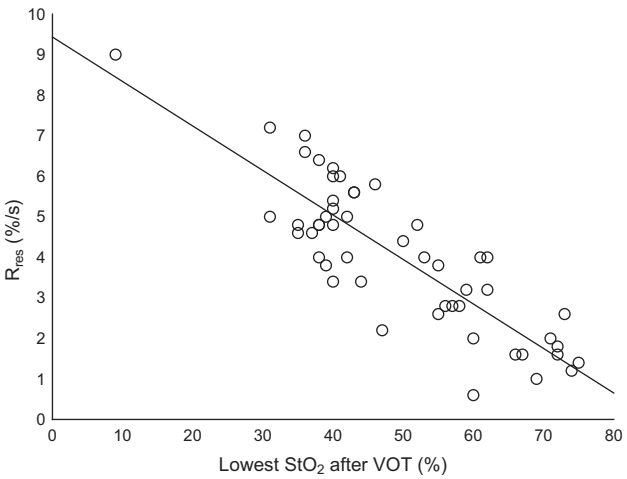
Results

In total, 9 healthy volunteers participated in the dynamic (VOT) measurements. The characteristics of the volunteers in the VOT studies are shown in Table 1.

Measured values

At baseline, mean StO_2 was 80% (SD, 5%) and mean THI was 13.7 (SD, 1.9). StO_2 and THI decreased during the VOT, followed by rapid increase and overshoot after reperfusion (Figure 1A and Figure 2A). Mean StO_2 at baseline in the 3-minute VOT was lower than in the 40% VOT group (83% [SD, 4%] v 77% [SD, 4%]; $P < 0.001$). The lowest mean StO_2 values at the end of the VOT were 69% (SD, 5%), 56% (SD, 6%), 39% (SD, 13%) and 39% (SD, 2%) in the 1-, 2-, 3-minute and 40% StO_2 VOTs, respectively. The lowest mean THI values at the end of the VOTs were 12.4 (SD, 2.4), 12.2 (SD, 1.2), 11.2 (SD, 2.3) and 12.3 (SD, 1.5) in the 1-, 2-, 3-minute and 40% StO_2 VOTs, respectively.

Figure 3. The relationship between lowest StO_2 during VOT and consecutive R_{res} during reperfusion

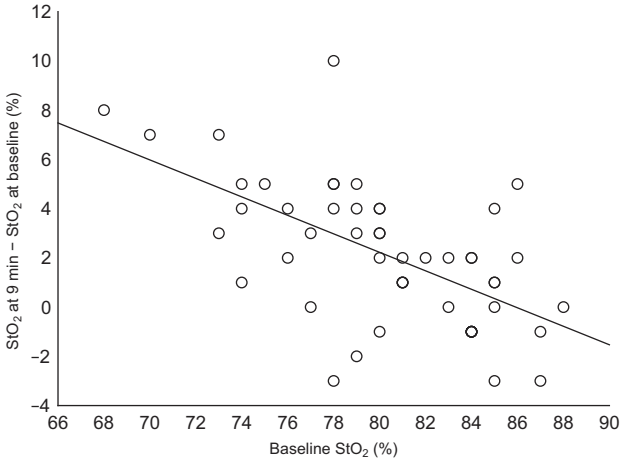


Spearman rank correlation coefficient (ρ) = – 0.8536; P < 0.001; coefficient of determination (R^2) = 0.7287.

R_{res} = rate of StO_2 increase. VOT = vascular occlusion test.

The StO_2 curves (change in value from baseline to end of experiment) differed between the VOTs (time-group interaction $P < 0.001$) (Figure 1A). The delta StO_2 from baseline to 9 minutes was greater for the 3-minute VOT than for the 40% StO_2 VOT ($P \leq 0.001$) (Figure 1B) with greater and more sustained relative hyperaemia in the 3-minute VOT.

Figure 4. The relationship between the baseline StO_2 and StO_2 at 9 minutes of observation after VOT



Spearman rank correlation coefficient (ρ) = – 0.5974; P < 0.001; coefficient of determination (R^2) = 0.3569.

VOT = vascular occlusion test.

The THI curves during the experiment differed between the VOTs (time-group interaction, $P < 0.001$) (Figure 2A). Although the delta THI did not differ between the 3-minute VOT and the 40% StO_2 VOT, the THI curves had a different time course (time-group interaction, $P = 0.002$) such that late after reperfusion, the 3-minute VOT was associated with greater THI values (Figure 2B).

Derived values

In the 40% StO_2 VOT the duration of occlusion ranged from 1:35 to 8:21 minutes (median, 3:29 minutes [IQR, 3:22–4:38 minutes]).

The mean amplitude of the ischaemia–reperfusion response was 19% (SD, 3.5%), 37% (SD, 6.3%), 55% (SD, 14.0%) and 56% (SD, 3.8%) in the 1-, 2-, 3-and 40% StO_2 VOTs, respectively. There was no difference in the rate of StO_2 decrease during vascular occlusion between groups. The overall mean rate of StO_2 decrease during vascular occlusion was 0.20%/s (SD, 0.06%/s). In contrast, the R_{res} was 1.6%/s (SD, 0.5%/s), 3.8%/s (SD, 1.0%/s), 5.1%/s (SD, 2.0%/s) and 5.1%/s (SD, 1.0%/s) for the 1-, 2-, 3-minute and 40% StO_2 VOT, respectively. There was no difference in the absolute deviation from the mean in R_{res} for the 3-minute and the 40% StO_2 VOTs. The R_{res} correlated with the lowest StO_2 at the end of the VOT ($R^2 = 0.73$) (Figure 3).

The mean tVO_2 was 2.3 (SD, 0.6), 2.9 (SD, 0.8), 2.8 (SD, 0.8) and 2.7 (SD, 0.8) in the 1-, 2-, 3-minute and 40% StO_2 VOTs, respectively.

The mean hyperaemia after occlusion was 36% × minute (SD, 10% × minute), 56% × minute (SD, 15% × minute), 73% × minute (SD, 17%% × minute) and 53% × minute (SD, 14% × minute) in the 1-, 2-, 3-minute and 40% StO_2 VOTs, respectively.

Additional assessments

Median NRS was 2 (IQR, 0–4), 2.5 (IQR, 1–4), 3.5 (IQR 2.5–5.5) and 4 (IQR 2–4) for the 1-, 2-, 3- and 40% StO_2 VOTs, respectively. NRS of 7 or over was reported in four experiments; two in the 3-minute VOT and two in the 40% StO_2 VOT. The maximum NRS was 8, and was reported in the 40% StO_2 VOT. The correlation between pain and the occlusion time was R = 0.37.

Return to stable baseline and right–left arm comparisons

Overall, the StO_2 did not return to baseline at 9 minutes after occlusion even for a 1-minute VOT, with a median increase in StO_2 of 2% (IQR, 0–4%; $P < 0.01$), which correlated negatively with baseline StO_2 level (R = – 0.60) (Figure 4). THI, conversely, returned to baseline values by the end of the experiment.

There was no difference in StO_2 (mean bias, 0.28%; 95% CI, 6.9%–7.5%), THI (mean bias – 0.26; 95% CI, – 3.5 to 3.0), rate of StO_2 decrease during vascular occlusion (mean bias, – 0.036%/minute; 95% CI, – 0.19 to 0.12/minute), tVO_2 (mean bias – 0.49; 95% CI, – 2.7 to 1.8), R_{res} (mean bias, 0.36%/minute; 95% CI, – 1.1 to 1.8%/minute) or the StO_2 maximum – minimum (mean bias, 2.2%; 95% CI, – 6.7 to 11.2%) between the right and the left arm.

Discussion

We found that increasing VOT duration from 1 to 3 minutes induces a greater ischaemia–reperfusion response, and that the signal obtained with short VOTs (1 and 2 minutes) is of limited and suboptimal intensity. While longer vascular occlusion during VOT increased the steepness of R_{res}, it did not affect estimation of tVO_2. When comparing the 3-minute VOT to the 40% StO_2 VOT, most assessment variables were similar; however, the 40% StO_2 targeted VOT took longer and the level of pain increased with the length of the vascular occlusion. Additionally, we found that application of a VOT alters the circulation of the thenar eminence for a period of time. Even after 1 minute of vascular occlusion, StO_2 values are higher than at baseline values for at least 9 minutes. Finally, we compared both arms and found that the reproducibility of StO_2, THI, the rate of StO_2 decrease during vascular occlusion, tVO_2 and R_{res} levels is high.

Both time-targeted[14-16] and StO_2-targeted[5,17-19] protocols have been used in VOT protocols to elicit an adequate ischaemia–reperfusion response. Both methods have their advocates and there is an ongoing discussion on the

optimal length of the VOT.[10,12] As NIRSth is now being used in many centres, understanding the factors affecting NIRSth variables obtained at VOT is of importance.[19-22] Mayeur and colleagues have argued that a 40% StO_2-targeted VOT is necessary for optimal diagnostic value.[11] In their study, however, the lowest mean StO_2 for the 3-minute VOT was 52% (SD, 10%) compared with 40% in the 40% StO_2 VOT.[11] In contrast, in our study, the mean StO_2 levels at the end of the vascular occlusion were 39% (SD, 13%) in the 3-minute VOT and 39% (SD, 2.2%) in the 40% StO_2 VOT. Furthermore, in several other studies, there was no difference in the spread of R_{res}, the most frequently reported dynamic NIRSth variable,[5,11,15,18,23-25] between the 3-minute VOT and the 40% StO_2 VOT.

Differences in the cohorts used in several studies could explain some of the above variations. However, given that ethnicity, sex and age of the volunteers in our experiments were heterogeneous and that the variance of most variables in our investigation are in line with other studies,[5,11,18] this seems unlikely. Differences in the NIRS device appear more likely to explain such variability[15] as the data generated by different NIRS devices can vary considerably.[26] Moreover, technical differences could also account for the narrower data spread observed in our study. For example, the coefficient of determination for R_{res} versus the lowest StO_2 at the end of the VOT was higher ($R^2 = 0.73$) in our study than in a previous study ($R^2 = 0.46$).[11] These observations suggest that technique-related differences or technology-related differences can deliver different perceptions of the relative intensity of a 3-minute versus 40% StO_2 VOT.

Irrespective of technology, the discomfort during VOT can be significant, and may limit the usefulness of VOT in non-sedated patients. The data from the current study suggest that the discomfort might increase with longer VOT, although individual variation is considerable. Others have also reported that long vascular occlusion times could lead to inability to complete VOT procedure due to patient discomfort.[5] In this regard, the time to perform VOT, thus the exposure to pain, was shorter for the 3-minute VOT. Moreover, some of the highest individual pain scores were reported for the 40% StO_2 VOT.

When repeated measurements of StO_2 and THI were performed before and after VOT, these variables showed bias with higher baseline levels after VOT. This post-ischaemic hyperaemic response is triggered even by a short vascular occlusion. However, its extent appears limited, with the greatest impact seen when baseline StO_2 is low. Such an effect could explain why the hyperaemia after 3-minute VOT was greater than in the 40% StO_2 VOT group, as the baseline 3-minute VOT was lower than in the 40% StO_2 VOT group. A study in trauma patients did not reveal changes in dynamic NIRSth variables on repeated measurement.[5]

Finally, StO_2 and THI values in the current study were all in same range reported by others with comparable NIRS probes.[11,18,24] As our VOT measurements indicated that repeated measurements could influence subsequent NIRS variables, we used the contralateral arm as a control to test reproducibility. Apart from technical specifications from the manufacturer, the data on this aspect of NIRSth are limited particularly for VOT. In our study, we demonstrated that bias was minimal for static and dynamic NIRSth-related variables.

Systemic, regional and local factors influence blood flow and oxygen consumption, and hence the StO_2 and THI measured in the thenar muscles.[27] Therefore, low spot StO_2 values may or may not indicate inadequate circulation.[15] Thus, the reactivity of the circulation to an ischaemic insult (VOT) is of greater interest in differentiating a normal from a pathological microcirculation.[5,23,24] Reperfusion increases StO_2 and THI levels under normal conditions, implying that not only blood flow increases in the thenar muscles, but also thenar haemoglobin increases, probably due to vasodilatation. Furthermore, a recent study reports that the R_{res} could be useful in optimising the rate of noradrenaline infusion in septic patients,[28] thus emphasising that performing VOT accurately is of importance. Data from a previous study suggest that maximal response is achieved when the VOT is performed to 40% StO_2.[11] In contrast, our data suggest that the 3-minute VOT generates information that is as robust as the 40% StO_2 VOT. Accordingly, the potential for any extra information given by the longer 40% StO_2 VOT must be balanced by the discomfort that such extended vascular occlusion causes. Importantly, in septic patients, reaching 40% StO_2 during VOT can take up to 10 minutes or more.[11] Ultimately, the longer the VOT takes, the less likely it will be performed regularly in clinical practice. This is because the ability to plan a diagnostic procedure by knowing its duration before execution helps with its integration into daily practice and with patient acceptance of any associated discomfort. The likelihood that the VOT will be adopted as a clinical method will increase if the test causes minimal discomfort and can be performed reasonably quickly. In this regard, as shown in our study, the 3-minute VOT carries advantage over the 40% StO_2 VOT.

Making the VOT comfortable, rapid and less labour-intensive, such as might be the case with venous occlusion,[29] is of importance for future integration of NIRSth into daily clinical practice and requires further investigation.

Conclusions

In summary, short VOT times (1 or 2 minutes) do not appear sufficiently robust to use as tests for the microcirculation. Any VOT alters the circulation of the thenar eminence, an effect that should be considered when repeating VOT within the same arm. The reproducibility of NIRS variables

of the thenar eminence is sufficient for clinical practice. Comparison of the 3-minute VOT and 40% StO_2 VOT suggests small differences in average intensity between the two. However, the latter method takes longer to perform with considerable discomfort for the longest measurements, without convincing advantages or evidence of greater intensity, making the 3-minute test a more practical approach to the routine clinical use of NIRSth.

Several additional technical studies need to be completed to define the best NIRSth protocol in intensive care patients.

Competing interests

None declared.

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