Near-infrared spectroscopy of the thenar eminence to estimate forearm blood flow

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ABSTRACT

Background: Near-infrared spectroscopy of the thenar eminence (NIRSth) can be used at the bedside to assess tissue oxygenation (Sto_2), the reperfusion response to ischaemia and the tissue haemoglobin index (THI). Its ability to estimate forearm blood flow (FBF) has not previously been assessed.

Objectives: We aimed to test whether short-lived venous occlusion-induced changes in NIRSth-derived THI (ΔTHI/minute) correlate with strain gauge plethysmography (SGP) measurements.

Methods: We measured FBF in nine volunteers with SGP by venous occlusion, while estimating ΔTHI. Measurements were obtained in two forearm positions (elevated and horizontal) at baseline and during induced hyperaemia.

Results: We performed 246 paired measurements at rest and after occlusion-induced hyperaemia. At rest, mean SGP-estimated FBF was 3.5–3.6 mL/dL/minute at baseline, compared with 12.9–13.6 mL/dL/minute during hyperaemia. At rest, ΔTHI was 6.1–8.2/minute, compared with 29.7–32.5/minute during hyperaemia. ΔTHI was a significant predictor of SGP FBF ($P < 0.01$), with stronger correlation during hyperaemia ($P < 0.01$). An equation was developed to convert ΔTHI/minute into FBF at mL/dL/minute ($FBF = 0.362 \times \Delta THI/minute + 0.864$).

Conclusions: NIRSth can be used to estimate FBF. Given its portability and its ability to also measure Sto_2 and vascular reactivity, NIRSth can assist in providing a comprehensive bedside assessment of the forearm circulation in critically ill patients.

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Near-infrared spectroscopy of the thenar eminence (NIRSth) can estimate tissue oxygenation (Sto_2) and the microvascular response to induced short-lived ischaemia.[1,2] NIRSth also provides information on the tissue haemoglobin index (THI). Changes in THI during short-lived venous occlusion (representative of the speed at which blood pooling occurs) can theoretically be used to estimate forearm blood flow (FBF).[3] Thus, NIRSth may provide a non-invasive bedside technique to assess the forearm circulation.

Strain gauge plethysmography (SGP) studies have shown that near-infrared spectroscopy (NIRS) of the *forearm* can estimate FBF using changes in the THI (ΔTHI),[3-6] but NIRSth in now preferred in the intensive care unit.[7,8] No studies have confirmed or refuted whether NIRS of the *thenar eminence* can be used to estimate FBF.[9,10] Additionally, as the THI changes represent blood pooling, which should occur in the most dependent segment of the arm,[11] elevation of the arm performed in previous SGP might influence the ability of NIRSth to detect these changes in THI.

We hypothesised that changes in THI would correlate with FBF measured by SGP, that both NIRSth and SGP would be able to detect higher rates of FBF during hyperaemia, and that arm position would have an effect on NIRSth measurements.

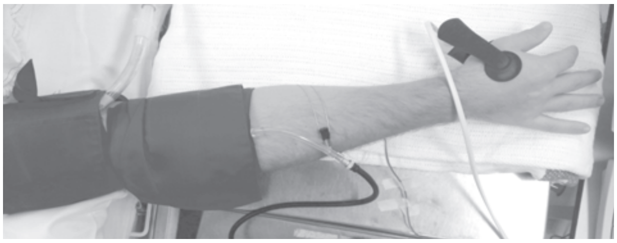
Methods

We performed a comparative crossover study in nine healthy volunteers, simultaneously assessing FBF as measured by SGP and NIRSth-derived ΔTHI/minute in both arms. The Monash University ethics committee approved our study (approval 2012001205).

The participants fasted and abstained from caffeine for 6 hours.[12] We placed a venous cuff on the upper arm (E20 rapid cuff inflator, Hokanson). Immediately distal to the venous cuff, we placed a manual blood pressure cuff to induce arterial occlusion. The strain gauge plethysmograph (EC6 strain gauge and photo plethysmograph, Hokanson) was placed at the midpoint of the forearm, and the near-infrared spectrometer (InSpectra 325, Hutchinson Technology) was placed on the thenar eminence (Figure 1). A purpose-built apparatus was used to produce forearm elevation when required. We made four measurements at baseline, and three measurements during induced reactive hyperaemia, using 30-second venous occlusions (at 40 mmHg) and 30-second recovery periods. Reactive hyperaemia was induced by a 3-minute, 200 mmHg venous occlusion.[2] FBF was estimated in each arm in the horizontal and elevated positions.

Analysis of SGP recordings was performed using PowerLab 2005 (ADInstruments). The average slope for the steepest segment of the curve was determined for a period

Figure 1. Experimental set-up, normal arm position*



* Arm pronated, venous cuff placed as proximal as possible on the upper arm and connected to a rapid cuff inflator (40 mmHg). Manually controlled blood pressure cuff placed distal to the venous cuff to induce arterial occlusion (200 mmHg). Strain gauge plethysmograph placed at midpoint of forearm. Near-infrared spectroscopy sensor placed on thenar eminence.

after initial cuff inflation and extrapolated for 1 minute to give a flow in mL/dL/minute. THI was recorded every 5 seconds during venous occlusion. The greatest THI increase for any 5-second period during a venous occlusion was used as the estimate of FBF for that occlusion cycle, and extrapolated to 1 minute, using the equation:

$$\text{FBF (THI/minute)} = [\text{maximum}\ (\text{THI}_x - \text{THI}_{x-5})]/5 \times 60$$

in which FBF is forearm blood flow, THI is tissue haemoglobin index, and x and x–5 represent two time points 5 seconds apart (used to determine the THI increase for each 5-second period). The maximum function is then used to determine the greatest THI change for any 5-second period (excluding the first 5 seconds). This maximum ΔTHI in 5 seconds is divided by five to produce THI/second, which is multiplied by 60 to produce THI/minute.

Statistical analysis

Statistical analysis was performed using SPSS, version 11 (IBM Corporation) and SAS 9.2 (SAS Institute). Some data were transformed using logarithmic transformation. Non-transformed non-parametric data were used, they are presented with the median and range or interquartile range. Repeated measures analysis of variance (ANOVA) were used to assess similarity at baseline and to determine if hyperaemia induced a detectable change in FBF. A mixed linear model was applied to establish the relationship between logNIRSth and logSGP. This mixed linear model was defined with logSGP as the outcome and the following prediction variables: logNIRSth; age; sex; arm side (left or right); phase (baseline or hyperaemia); and interaction between arm position (horizontal or elevated) and phase. Interaction terms were fitted between logNIRSth and phase, and between logNIRSth and arm position. Linear regression was used to determine a simplified equation to enable conversion from NIRSth-derived THI changes into a unit of flow.

To determine if arm position had an effect, paired *t* tests and Wilcoxon matched-pairs signed-rank tests were used. Baseline and hyperaemia were considered as one group set, and then baseline and hyperaemia were analysed as separate groups.

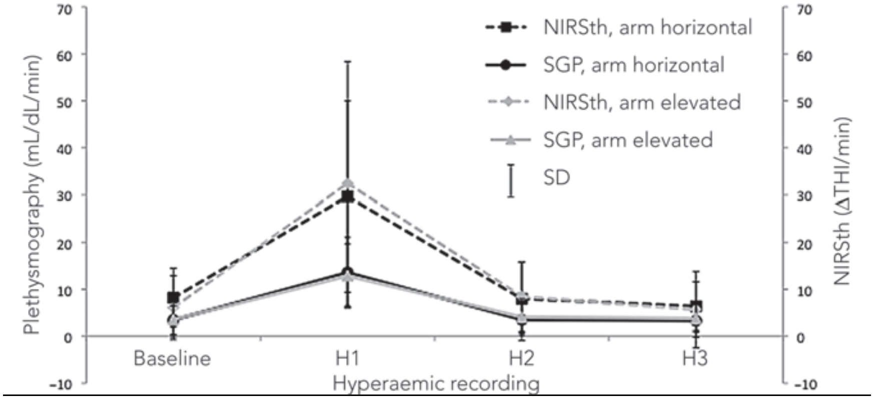
Results

The nine volunteers (including five men) had a median age of 23 years (range, 22–32 years) and median body mass index of 22.7 kg/m^2 (range, 19.3–26.8 kg/m^2).

Horizontal-arm mean SGP-derived FBF was 3.5 mL/dL/minute (SD,1.5 mL/dL/minute) at baseline and 13.6 mL/dL/minute (SD, 3.7 mL/dL/minute) during hyperaemia. Elevated-arm mean FBF was 3.6 mL/dL/minute (SD, 1.6 mL/dL/minute) at baseline, and 12.9 mL/dL/minute (SD, 3.4 mL/dL/minute) during hyperaemia.

Horizontal NIRSth-derived mean ΔTHI was 8.2/minute (SD, 3.1/minute) at baseline, and 29.7/minute (SD, 10.2/minute) during hyperaemia. Elevated ΔTHI was 6.1/minute (SD, 3.2/minute) at baseline, and 32.5/minute (SD, 13/minute) during hyperaemia. At baseline, there was no significant difference in measurements obtained in the horizontal position compared with the elevated position. In all combinations of device positions, the first hyperaemic

Figure 2. Hyperaemia estimated by a baseline recording and three hyperaemic recordings, using SGP and NIRSth



SGP = strain guage plethysmography. NIRSth = near-infrared spectroscopy of thenar eminence. THI = tissue haemoglobin index. H1 = first hyperaemic recording. H2 = second hyperaemic recording. H3 = third hyperaemic recording.

Table 1. Effect of forearm position on FBF estimates

FBF	FBF affected for NIRSth	FBF affected for SGP
Combined	Yes ($P < 0.01$)	No effect detected ($P = 0.2$)
Baseline	Yes ($P < 0.01$)	No effect detected ($P > 0.9$)
B_{mean}	Yes ($P = 0.03$)	No effect detected ($P > 0.9$)

FBF = forearm blood flow. NIRSth = near-infrared spectroscopy of thenar eminence. SGP = strain gauge plethysmography. B_{mean} = mean baseline recording.

recording of FBF (H1) was significantly different from the mean baseline recording (B_{mean}) ($P < 0.001$) (Figure 2).

LogNIRSth ($P < 0.01$), arm position ($P < 0.01$) and phase ($P < 0.01$) were independent predictors of logSGP (Figure 3). There was a significant interaction between logNIRSth, and phase ($P < 0.01$), indicating that the strength of the relationship between logNIRSth and logSGP was significantly greater in the hyperaemic phase than at baseline ($P < 0.01$). There was a trend towards an interaction between logNIRSth and arm position ($P = 0.07$).

The regression equation to convert ΔTHI/minute to mL/dL/minute was:

$$\text{FBF (mL/dL/minute)} = 0.362\ (\pm 0.044)\ \Delta\text{THI/minute} + 0.864\ (\pm 0.642)\ (P < 0.01)$$

in which FBF is forearm blood flow and ΔTHI/minute is the NIRSth-derived THI change. Table 1 indicates whether arm position influenced FBF estimates.

Discussion

We performed a comparative crossover study in healthy volunteers to test whether NIRSth can estimate SGP-derived FBF. We also aimed to determine the effect of arm position on the relationship between NIRSth and SGP, and on the results obtained with each method. We found that NIRSth-derived changes in THI were independent predictors of SGP-derived FBF, and their correlation was stronger during hyperaemia. We developed an equation to convert ΔTHI changes into SGP-FBF measurements with an acceptable degree of accuracy. Additionally, we found that arm position had an effect on the estimation of ΔTHI.

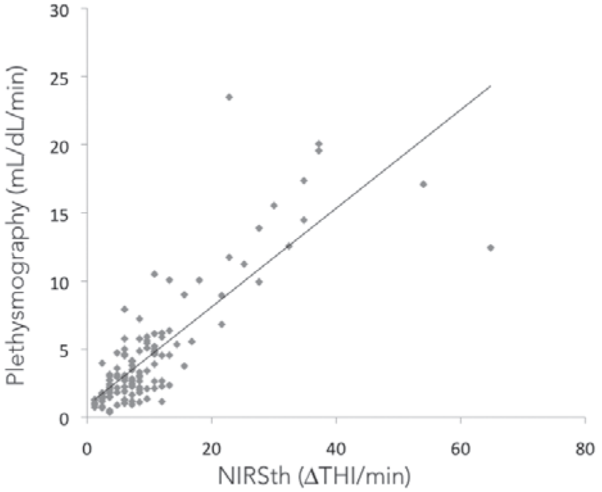
Previous studies

The value of NIRS of the forearm to estimate FBF and SGP has been previously assessed,[3-6] and some studies have used NIRS as the primary means of assessing blood flow.[13,14] However, no studies have compared the new technology of NIRS of the thenar eminence to SGP. Although our SGP-derived FBF values are consistent with previous studies, we are unable to compare NIRSth estimations with previous studies due to a proprietary algorithm.[3,15] Previous studies also assessed the effect of wrist occlusion and found no difference between FBF estimation with or without wrist occlusion.[10] This is important, as estimation of ΔTHI with NIRSth would not have been possible with wrist occlusion.

Additionally, the impact of elevation of the arm to promote venous drainage during SGP has not been rigorously tested. We hypothesised that elevation of the arm would result in blood pooling in the area of tissue adjacent to the collecting cuff under the influence of gravity. As the SGP was placed proximal to the NIRSth probe, this proximal pooling could influence results. In contrast, we proposed that with the arm in the horizontal position, blood would collect evenly throughout the arm and this pooling effect would be eliminated. As we intend to apply this technique in critically ill patients, for whom the horizontal arm position is preferred, we aimed to show that elevation of the arm would influence the result but would not be necessary to develop a predictive equation.

We found that the arm position did influence estimations of THI, as predicted, but did not influence SGP, and that we could derive a conversion equation for the horizontal position.

Figure 3. Relationship between forearm blood flow (elevated forearm) measured by strain gauge plethysmography and NIRSth-derived THI changes*



*No correlation coefficients presented; repeated-measures statistics were applied to data assessment. NIRSth = near-infrared spectroscopy of thenar eminence. THI = tissue haemoglobin index.

Strengths and limitations

Our study was performed in a controlled environment using the same simultaneous and bilateral procedures and equipment for every participant. We studied participants who were different from ICU patients, our final target population; however, this was an initial exploratory proof-of-concept study. We were unable to calculate a measurement of flow to directly compare with SGP, and these results can only be applied to similar NIRSth models, but the underlying physiology should be independent of the NIRSth device. Additionally, the NIRSth device we used had limited sensitivity in that it only reported the THI to one decimal place. Increased sensitivity may improve the accuracy of FBF NIRSth estimation.

Further research in this area will involve validation studies in critically ill patients, perhaps using Doppler ultrasound to estimate FBF and comparing it to NIRSth-derived equations.

Conclusions

We describe a relationship between NIRSth-derived THI and FBF in healthy volunteers that allows estimation of FBF in different operative conditions. Our findings justify further investigation of these estimates in critically ill patients.

Competing interests

None declared.

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