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Research

Simultaneous multi-depth assessment of tissue oxygen saturation in the thenar and forearm using near-infrared spectroscopy during a simple cardiovascular challenge

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Abstract

Introduction: Hypovolemia and hypovolemic shock are life-threatening conditions that occur in numerous clinical scenarios. Near-infrared spectroscopy (NIRS) has been widely explored, successfully and unsuccessfully, in an attempt to use it as an early detector of hypovolemia by measuring tissue oxygen saturation (StO₂). In order to investigate the measurement site dependence and probe dependence of NIRS in response to hemodynamic changes, such as hypovolemia, we applied a simple cardiovascular challenge: a posture change from supine to upright, causing a decrease in stroke volume (as in hypovolemia) and a heart rate increase in combination with peripheral vasoconstriction to maintain adequate blood pressure.

Methods: Multi-depth NIRS was used in nine healthy volunteers to assess changes in StO₂ in the thenar and forearm in response to the hemodynamic changes associated with a posture change from supine to upright.

Results: A posture change from supine to upright resulted in a significant increase ($P < 0.001$) in heart rate. Thenar StO₂ did not respond to the hemodynamic changes following the posture change, whereas forearm StO₂ did. Forearm StO₂ was significantly lower ($P < 0.001$) in the upright position compared to supine for all probing depths.

Conclusion: The primary findings in this study were that forearm StO₂ is a more sensitive parameter to hemodynamic changes than thenar StO₂ and that the depth at which StO₂ is measured is of minor influence. Our data support the use of forearm StO₂ as a sensitive parameter for the detection of central hypovolemia and hypovolemic shock in (trauma) patients.

Introduction

Hypovolemia and hypovolemic shock are life-threatening conditions that occur in numerous clinical scenarios such as in the emergency room, during surgery, and in intensive care patients [1-4]. Compensatory mechanisms that protect against alterations in blood pressure make standard hemodynamic measurements poor indicators for early assessment of hypovolemia and shock. One of these compensatory mechanisms is extreme peripheral vasoconstriction, and therefore measurement of alterations in the peripheral circulation could aid in the early detection of hypovolemia.

To this end, near-infrared spectroscopy (NIRS) – an optical technique for measuring tissue oxygen saturation – has been widely explored, successfully and unsuccessfully, in attempts to identify the severity of hypovolemia [5-8], to monitor blood loss [9-11] and guide resuscitation [12-14], and to predict patient outcome [15-17]. The main problem with the interpretation of tissue oxygen saturation (StO₂) data from these studies, however, is the diversity of methodologies used for assessing StO₂. Two major aspects regarding the inconsistent methodology are the application site and the probing depth. The application site is important because differences may exist in the sensitivity of underlying muscle groups and other anatomical structures to cardiovascular challenges such as central hypovolemia. The probing depth, additionally, determines the relative contribution of muscular and (sub)dermal tissue to the StO₂ measurement.

ANOVA = analysis of variance; LBNP = lower body negative pressure; NIRS = near-infrared spectroscopy; StO₂ = tissue oxygen saturation.

Although it is often discussed that these aspects affect the assessment of StO_2 , no studies have simultaneously measured StO_2 in the thenar and forearm at multiple depths. In order to investigate the actual measurement site dependence and probe dependence of NIRS in response to hemodynamic changes, such as hypovolemia, we applied a simple cardiovascular challenge: a posture change from supine to upright, causing a decrease in stroke volume (as in hypovolemia) and a heart rate increase in combination with peripheral vasoconstriction to maintain adequate blood pressure [18-22]. Multi-depth NIRS was used to assess changes in StO_2 in the thenar and forearm in response to the hemodynamic changes associated with the described cardiovascular challenge.

Materials and methods

Subjects

The study protocol was approved by the Medical Ethics Committee of University College London. Nine healthy, normotensive volunteers who were not receiving any vasoactive medication were requested to refrain from consuming caffeine-containing beverages prior to the measurements. The room temperature was maintained at $20 \pm 1^\circ\text{C}$.

Hemodynamic monitoring

Prior to the experimental protocol, systolic and diastolic blood pressures were measured in the supine position using an automatic blood pressure cuff around the upper arm (type M5-I, Omron Matsusaka Co. Ltd, Japan). The heart rate was continuously monitored during the entire experimental protocol, using a fingertip pulse oximeter (Defibron, Groningen, the Netherlands).

Near-infrared spectroscopy

StO_2 was non-invasively and simultaneously measured in the thenar and forearm by applying one multi-depth NIRS probe on the skin of the thenar eminence and one multi-depth NIRS probe on the lateral side of the anterior surface of the forearm brachioradialis muscle, both placed in parallel to the orientation of the respective target muscle groups (Hutchinson Technology, Hutchinson, MN, USA). The NIRS devices employ reflectance mode probes that have one 1.5 mm optical fiber to illuminate the tissue and two optical fibers to detect the backscattered light from the tissue. The spatial separation between the illumination fiber and the two detection fibers is 15 mm and 25 mm, respectively. As described by Cui and colleagues, the NIRS measurement depth increases with increasing distance between the illuminating and detecting fibers [23]. The 25 mm separated fiber therefore measures a greater and deeper tissue volume than the 15 mm separated fiber. By subtracting the spectral absorbance measured by the 15 mm fiber from that measured by the 25 mm fiber, similar to the NIRS device used by the group of Torella and colleagues [9,10], the spectral absorbance between these two probing depths was determined and used to calculate StO_2 in this isolated layer of tissue.

The relative optical attenuation of the backscattered light at four wavelengths (680 nm, 720 nm, 760 nm, and 800 nm) was measured for each probing depth to calculate two second-derivative attenuation values, one centered at 720 nm and the other at 760 nm [24]. A ratio of the 720 nm to 760 nm second-derivative values is directly related to StO_2 , defined as $[\text{HbO}_2]/([\text{Hb}] + [\text{HbO}_2])$, via a calibration table that is permanently stored within the device [25].

Experimental protocol

Subjects started the experiment in a supine position. After stable baseline traces were obtained for the heart rate and NIRS measurements, the subjects changed posture to an upright position. Fifteen minutes later, the subjects changed posture back to supine. The heart rate and StO_2 data were obtained during the supine position, then upright for 5 and 15 minutes, and again in the supine position. The hand and forearm were kept at heart level during the entire experimental protocol using a sling.

Statistical analysis

Statistical analysis was performed in GraphPad Prism software (GraphPad Software, San Diego, CA, USA). Normal distribution of the data was confirmed for each StO_2 parameter (15 mm, 25 mm, and 25 – 15 mm) using the D'Agostino and Pearson omnibus normality test. Comparative analysis between groups was performed using analysis of variance (ANOVA) with a Bonferroni post-hoc test. All data are presented as the mean \pm standard deviation. Differences between groups with $P < 0.05$ were considered statistically significant.

Results

Subject demographics

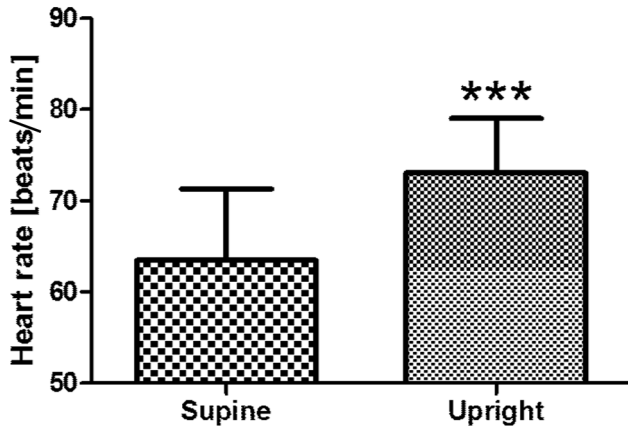
The subject population consisted of six females and three males (all Caucasian) with a mean \pm standard deviation age of 39 ± 14 years, height of 171 ± 6 cm, and weight of 70 ± 8 kg. Systolic and diastolic blood pressures were 110 ± 8 and 69 ± 7 mmHg, respectively.

Heart rate and StO_2

No differences in heart rate and StO_2 values between the first and second supine time points (beginning and the end of the experimental protocol, respectively) and between the first and second upright time points (after 5 and 15 minutes upright, respectively) were observed. The data were therefore categorized into supine and upright.

Repeated-measures ANOVA showed that a posture change from supine to upright resulted in a significant increase in heart rate (Figure 1). Furthermore, thenar StO_2 did not respond to the hemodynamic changes following the posture change (Figure 2, left), whereas forearm StO_2 did (Figure 2, right). In the forearm, StO_2 was significantly lower ($P < 0.001$) in the upright position with respect to the supine position. StO_2 measured in the supine position was significantly higher

Figure 1



Heart rate in the supine and upright positions. *** $P < 0.001$ for upright versus supine position.

in the thenar than in the forearm ($P < 0.05$ for the 15 mm and 25 mm probing depths and $P < 0.001$ for the 25 – 15 mm probing depth). In the forearm, the mean \pm standard deviation change in StO_2 was 7.1 ± 4.0 for 15 mm, 8.6 ± 4.5 for 25 mm, and 10.9 ± 6.0 for 25 – 15 mm probing depth, respectively.

Regular ANOVA (not repeated measures) revealed no significant differences between supine and upright positions for either the thenar or the forearm for all probing depths, indicating that the change in StO_2 during the posture change from supine to upright (analyzed using repeated-measures ANOVA) is more important than the absolute StO_2 values for

monitoring the effects of hemodynamic changes on peripheral tissue oxygenation.

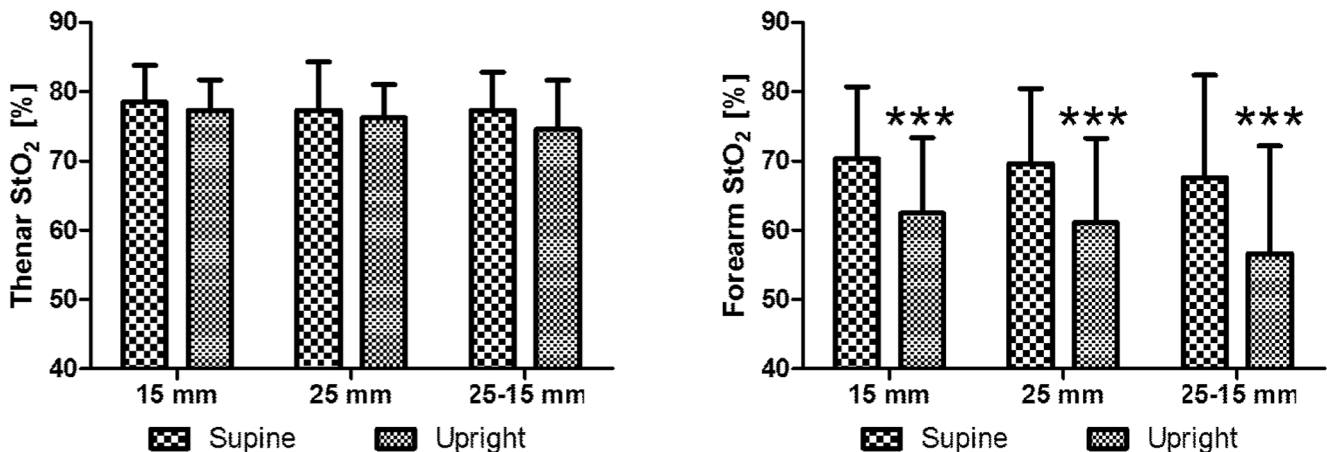
StO_2 values in the thenar during both supine and upright positions were similar in females and males, but in the forearm StO_2 values tended to be lower in females than in males (number too small for statistical analysis). The StO_2 decrease caused by a posture change from supine to upright, however, was of a similar extent in females and males for both the thenar and the forearm for all probing depths.

Discussion and conclusions

The present study investigated the application site dependence and probing depth dependence of NIRS measurements for the detection of changes in StO_2 following a simple cardiovascular challenge. The main findings were that forearm StO_2 is a more sensitive parameter to hemodynamic changes than thenar StO_2 and that the depth at which StO_2 is measured is of minor influence. In addition, our data indicated that the change in StO_2 during a cardiovascular challenge is more important than the absolute StO_2 values for monitoring the effects of hemodynamic changes on peripheral tissue oxygenation.

In the present study, a simple cardiovascular challenge was created by a posture change from supine to upright. This challenge is associated with a decrease in stroke volume, an increase in heart rate, and an increase in peripheral vascular tone in order to maintain adequate blood pressure. Since we did not measure the stroke volume and cardiac output we could not assess the extent of this cardiovascular challenge further than its effect on the heart rate. The observed increases in heart rate, however, indicate that the applied posture change did induce significant alterations at the

Figure 2



Thenar and forearm tissue oxygen saturation using different probe spacings. Thenar tissue oxygen saturation (StO_2) (left), and forearm StO_2 (right) in the supine and upright positions as measured using different probe spacings. *** $P < 0.001$ for upright versus supine position.

macrocirculatory level. This is supported by several studies investigating hemodynamic responses in healthy subjects undergoing passive upright tilt [18-22]. Furthermore, the focus of the present study was to investigate the capability of NIRS to detect alterations in StO₂ following macrocirculatory changes and, especially, the role of NIRS application site and probing depth. This capability we have evidently shown.

We have shown that forearm StO₂ is more responsive to hemodynamic changes than thenar StO₂. This is surprising given that the employed NIRS device is promoted for use on the thenar and not the forearm. Many researchers using NIRS technology claim that the contribution of (sub)dermal tissue to the NIRS signal is deleterious for its interpretation, and many optical and algorithmic solutions are explored to minimize this effect. Indeed, the present study shows that the standard deviation in distribution of StO₂ values obtained in the forearm is much larger compared with that in the thenar and, in addition, StO₂ values in the forearm tended to be lower in females than in males. Both these observations could be attributed to interindividual variability in the contribution of subdermal adipose tissue to the NIRS signal. The variance in forearm StO₂ appeared to be independent of probing depth, however, as the 15 mm, 25 mm, and 25 – 15 mm signals all provided very similar StO₂ values. Furthermore, the StO₂ change in response to the posture change was of similar extent for all probing depths. Taken together, these results suggest that the (micro)vascular response to a cardiovascular challenge might be similar in (sub)dermal tissue and in the muscle, and it is the forearm tissue as a whole that is more sensitive to hemodynamic changes compared to the thenar.

In a recent study by Soller and colleagues, where central hypovolemia was induced by lower body negative pressure (LBNP) [6], forearm StO₂ was measured using a device developed by the authors (equipped with a 30 mm probe) and was shown to be a sensitive parameter to the stroke volume decrease associated with application of LBNP. The stroke volume and forearm StO₂ decreased immediately at onset of simulated hypovolemia (LBNP = -15 mmHg), while the heart rate remained unresponsive until an LBNP of -45 mmHg and increased significantly at an LBNP of -60 mmHg. These data support our finding that forearm StO₂ is a sensitive measure to detect alterations in cardiovascular autonomic tone associated with central hypovolemia.

In a subsequent LBNP study by the same group [7], thenar StO₂ was measured with a device similar to the device used in the present study (HT device, 15 mm probe) and forearm StO₂ was measured using the device developed by the authors (30 mm probe). The authors found that their device on the forearm was more sensitive to hypovolemia than the HT device on the thenar, and concluded that their device had superior sensitivity to detect acute hypovolemia. The authors furthermore hypothesize that the 15 mm probe spacing of the

HT device is probably too small to collect light from a sufficiently deep layer of muscular tissue to detect hypovolemia and, additionally, it was suggested that the relatively large contribution of (sub)dermal tissue (due to the smaller probing depth) might affect the StO₂ measurements. The present study, however, where thenar and forearm StO₂ were measured at multiple depths simultaneously, clearly shows that forearm StO₂ is a more sensitive parameter to detect changes in cardiovascular autonomic tone than thenar StO₂ (both measured with the HT device), and that the sensitivity of these measurements was independent of probing depth.

Crookes and colleagues showed in a study in trauma patients that thenar StO₂ could be used to identify severe hypovolemic shock, but that it was unable to detect mild and moderate hypovolemic shock [5]. The patient population in that study was categorized into mild, moderate, and severe hypovolemic shock, where maximum heart rates were 108 ± 26 beats/minute, 118 ± 23 beats/minute, and 130 ± 35 beats/minute, respectively. Their finding that thenar StO₂ is insensitive to mild and moderate hypovolemic shock is supported by our data and, in addition, our data support the use of forearm StO₂ as a more sensitive parameter for the detection of central hypovolemia and hypovolemic shock in (trauma) patients.

In conclusion, the present study has shown that forearm StO₂ is more responsive to hemodynamic changes compared with thenar StO₂ and that the response is similar for the applied probing depths. In addition, our results indicate that the change in StO₂ during a cardiovascular challenge is more important than the absolute StO₂ values for monitoring the effects of hemodynamic changes on peripheral tissue oxygenation. Our data furthermore suggest that the (micro)vascular response to a cardiovascular challenge might be similar in (sub)dermal tissue and in the muscle, and that it is the forearm tissue as a whole that is more sensitive to hemodynamic changes compared to the thenar tissue. This hypothesis, however, warrants further investigation.

Competing interests

Multi-depth NIRS devices were provided by Hutchinson Technologies.

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