Brain Tissue Oxygenation in Patients with Septic Shock: a Feasibility Study

Michael Wood, Andy Song, David Maslove, Cathy Ferri, Daniel Howes, John Muscedere, J Gordon Boyd

ABSTRACT: Background: Delirium is common in critically ill patients and its presence is associated with increased mortality and increased likelihood of poor cognitive function among survivors. However, the cause of delirium is unknown. The purpose of this study was to demonstrate the feasibility of using near-infrared spectroscopy (NIRS) to assess brain tissue oxygenation in patients with septic shock who are at high risk of developing delirium. Methods: This prospective observational study was conducted in a 33-bed general medical surgical intensive care unit (ICU). Patients with severe sepsis or septic shock were eligible for recruitment. The FORESIGHT NIRS monitor was used to assess brain tissue oxygenation in the frontal lobes for the first 72 hours of ICU admission. Physiological data was also recorded. We used the Confusion Assessment Method-ICU to screen for delirium. Results: From March 1st 2014-September 30th 2014, 10 patients with septic shock were recruited. The NIRS monitor captured 81% of the available data. No adverse events were recorded. Brain tissue oxygenation demonstrated significant intra- and inter-individual variability in the way it correlated with physiological parameters, such as mean arterial pressure, heart rate, and peripheral oxygen saturation. Mean brain tissue oxygen levels were significantly lower in patients who were delirious for the majority of their ICU stay. Conclusion: It is feasible to record brain tissue oxygenation with NIRS in patients with septic shock. This study provides the infrastructure necessary for a larger prospective observational study to further examine the relationship between brain tissue oxygenation, physiological parameters, and acute neurological dysfunction.

RÉSUMÉ: Oxygénation tissulaire cérébrale chez les patients atteints de choc septique : une étude de faisabilité. Contexte : Le délire est fréquent chez les patients qui sont gravement malades et sa présence est associée à une mortalité accrue ainsi qu’à une probabilité accrue d’altération de la fonction cognitive chez les survivants. Cependant, la cause du délire demeure inconnue. Le but de cette étude était de démontrer la faisabilité d’utiliser la spectroscopie proche infrarouge (NIRS) pour évaluer l’oxygénation du tissu cérébral chez des patients en choc septique qui sont à haut risque de présenter un délire. Méthode : Nous avons effectué une étude observationnelle prospective dans une unité de soins intensifs (USI) médicaux et chirurgicaux de 33 lits. Les patients atteints de septicémie sévère ou de choc septique étaient éligibles à l’étude. Un moniteur FORESIGHT NIRS a été utilisé pour évaluer l’oxygénation du tissu cérébral des lobes frontaux au cours des 72 premières heures d’hospitalisation à l’USI. Nous avons recueilli les données physiologiques. Le Confusion Assessment Method-ICU a été utilisé pour dépister le délire. Résultats : Dix patients atteints de choc septique entre le 1er mars 2014 et le 30 septembre 2014 ont été inclus dans l’étude. Le moniteur NIRS a capté 81% des données disponibles. Aucun incident fâcheux n’a été observé. Nous avons noté une grande variabilité intra et inter individu dans la correlation entre l’oxygénation du tissu cérébral et les paramètres physiologiques comme la tension artérielle, le rythme cardiaque et la saturation périphérique en oxygène. Les niveaux d’oxygène du tissu cérébral étaient significativement inférieurs chez les patients qui étaient en délire pendant la plus grande partie de leur séjour à l’USI. Conclusion : Il est possible d’enregistrer l’oxygénation du tissu cérébral avec le NIRS chez des patients en choc septique. Cette étude indique quelle est l’infrastructure requise pour une étude observationnelle prospective de plus grande ampleur dans le but d’examiner davantage la relation entre l’oxygénation du tissu cérébral, les paramètres physiologiques et la dysfonction neurologique aiguë.

Keywords: Delirium, sepsis, near infrared spectroscopy, CAM-ICU, tissue oxygenation

doi:10.1017/cjn.2015.280


Severe sepsis and septic shock are commonly encountered by medical-surgical intensive care unit (ICU) staff with an incidence rate of 3 per 1000 population.1 In spite of modern therapeutic interventions, in-hospital mortality rates remain relatively high ranging from 15-20%.2-3 and long-term mortality rates as high as 57%.4 Severe sepsis frequently leads to the onset of delirium, which is defined as an “acute, fluctuating change in mental status, with inattention and altered levels of consciousness”.5 Prevalence of delirium is as high as 80% in critically ill patients5 and infection is a major etiological factor.6 The onset of delirium is associated with increased mortality, increased ICU length of stay, increased ventilator time7 and cognitive impairments amongst survivors.10-13 However, despite the clinical importance of delirium during severe sepsis/septic shock, its underlying cause has remained elusive.
Hypoperfusion and multi-organ dysfunction are prominent in this patient population. Most organ systems are monitored with a combination of clinical and biochemical indices. For example, renal perfusion is monitored by assessing urine output as well as plasma creatinine levels. However, there is currently no surrogate marker for cerebral perfusion. Therefore, a real-time measurement of cerebral oxygenation could act as this much-needed proxy for cerebral perfusion. Near infrared spectroscopy (NIRS) provides a simple, non-invasive, localized assessment of cerebral oxygenation. This measurement of cerebral oxygenation is promising as an indirect measurement of cerebral perfusion. It already correlates with other measures of cerebral perfusion, such as jugular venous bulb oxygen saturation, brain tissue oxygen tension, and computed tomography (CT) perfusion. Furthermore, using NIRS to monitor cerebral oxygenation during coronary artery bypass surgery has yielded promising results. Cerebral desaturations were avoided and led to significantly fewer incidences of organ dysfunction and a shorter length of ICU stay. Near infrared spectroscopy has also been used during carotid endarterectomy to monitor decreases in brain tissue oxygen levels as a possible warning of cerebral ischemia that may require an intervention such as shunting. Therefore, NIRS is a feasible, non-invasive strategy to monitor cerebral oxygenation that may correlate with clinically relevant outcomes.

The objective of this pilot study was to demonstrate the feasibility of using NIRS to provide long-term continuous measurements of cerebral oxygenation in critically ill patients with severe sepsis/septic shock. The overall aim of our research program is to test the hypothesis that poor brain tissue oxygenation (as a surrogate marker of cerebral perfusion) when patients are acutely and critically ill, places them at risk of developing delirium throughout their ICU stay. To assess this, our secondary outcomes explored the correlation between cerebral oxygenation and hemodynamic variables, as well as whether or not cerebral oxygenation correlated with the development of delirium in patients with severe sepsis/septic shock.

MATERIALS AND METHODS

Study design, patient selection, and treatment

This prospective observational study was performed in an academic 33-bed general medical/surgical intensive care unit that is the regional level 1 trauma centre and tertiary referral centre. The local Health Sciences Research Ethics Board approved the study protocol, which included deferred consent for 24 hours due to the non-invasive nature of the monitoring device. Patients were considered eligible if they were admitted to the ICU within 24 hours of meeting the Society of Critical Care Medicine’s criteria for either severe sepsis or septic shock, and were adult patients over the age of 17. Exclusion criteria included a life expectancy less than 24 hours, an underlying diagnosis of cognitive dysfunction (including dementia), or a reason that they may not be able to participate in follow-up (these patients are part of a larger cohort examining the long-term neurological effects of critical illness). The treatment of each patient was at the discretion of the attending intensive care physician. The treating physicians did not have access to the brain tissue oxygen (BtO2) levels.

Data collection

Enrolled patients had their hourly hemodynamic variables [e.g. systolic blood pressure (SBP), diastolic blood pressure (DBP), mean arterial pressure (MAP), heart rate (HR)], vasoactive, and sedative/analgesic medications recorded. Parameters measured from arterial blood gas, were recorded when ordered by the attending physician. Brain tissue oxygen levels were measured with the FORESIGHT monitor (CASMED, Caster Medical, Canada) equipped with the five cm sensor that was placed on the patients’ forehead which can report regional cerebral oxygenation at an approximate depth of two to three cm. The probe on the patient’s forehead emits varying wavelengths of infrared light (700-1000 nm), which pass through skin and bone with only minimal absorption. The light that returns to the sensor represents the amount of spectral absorption occurring in the tissue bed; venous circulation accounts for the majority (75-80%) of the NIRS signal. The sensor measures changes in oxy- and deoxygenated hemoglobin in brain tissue at the arteriole, capillary, and venule level. These changes are represented as absolute values of BtO2 that range from 0-99%, tend to remain fairly stable/persistent over time, and can be estimated during normocapnia and varying degrees of hypoxia. Scalp and skull signals are also measured from a second sensor, and subtracted from the overall signal using a proprietary algorithm. We began recording immediately after patient enrollment and BtO2 levels were measured by the monitor every two seconds for the first 72 hours of the patients’ ICU stay.

To screen for delirium, patients were assessed daily during their entire ICU stay with the Confusion Assessment Method (CAM)-ICU, a validated tool for detecting delirium in critically ill patients. One of the trained researchers performed the daily delirium screening at a time that was convenient for the patient, their family, and the medical team directing their care. However, there was not a systematic procedure to coordinate the time of day at which each patient was assessed.

Statistics

The primary outcome of this study was feasibility. We defined feasibility a priori as the ability to perform long-term (72-hour) continuous recordings of BtO2 levels in critically ill patients with severe sepsis and septic shock. Additional assessments of feasibility included 1) daily screening of the nursing staff to determine if the device was interfering with nursing care, procedures, or imaging, 2) enrollment rates, 3) consent rates, and 4) challenges with the consent process. Secondary outcomes assessed were the correlations between non-invasive measurements of BtO2 with hemodynamic and physiological parameters (including SBP, MAP, HR, peripheral oxygen saturation (SaO2) and partial pressure of carbon dioxide (pCO2)). This was performed by calculating linear correlation coefficients with GraphPad Prism (v6). To provide graphical representation of the correlation coefficients, a correlation plot was generated using the R software package. T-tests were used to determine if there were differences in physiological variables (including mean BtO2), sedative medications, and narcotics, between patients who were delirious for the majority of their ICU stay compared with patients who were not. Results of these comparisons were considered significant if p < 0.05. For these comparisons, the Bonferroni correction was used.

Role of device manufacturer

Caster Medical Systems provided the FORESIGHT NIRS monitor at no cost to the investigators. The disposable sensors were represented as absolute values of BtO2 that range from 0-99%, tend to remain fairly stable/persistent over time, and can be estimated during normocapnia and varying degrees of hypoxia. Scalp and skull signals are also measured from a second sensor, and subtracted from the overall signal using a proprietary algorithm. We began recording immediately after patient enrollment and BtO2 levels were measured by the monitor every two seconds for the first 72 hours of the patients’ ICU stay.

To screen for delirium, patients were assessed daily during their entire ICU stay with the Confusion Assessment Method (CAM)-ICU, a validated tool for detecting delirium in critically ill patients. One of the trained researchers performed the daily delirium screening at a time that was convenient for the patient, their family, and the medical team directing their care. However, there was not a systematic procedure to coordinate the time of day at which each patient was assessed.

The primary outcome of this study was feasibility. We defined feasibility a priori as the ability to perform long-term (72-hour) continuous recordings of BtO2 levels in critically ill patients with severe sepsis and septic shock. Additional assessments of feasibility included 1) daily screening of the nursing staff to determine if the device was interfering with nursing care, procedures, or imaging, 2) enrollment rates, 3) consent rates, and 4) challenges with the consent process. Secondary outcomes assessed were the correlations between non-invasive measurements of BtO2 with hemodynamic and physiological parameters (including SBP, MAP, HR, peripheral oxygen saturation (SaO2) and partial pressure of carbon dioxide (pCO2)). This was performed by calculating linear correlation coefficients with GraphPad Prism (v6). To provide graphical representation of the correlation coefficients, a correlation plot was generated using the R software package. T-tests were used to determine if there were differences in physiological variables (including mean BtO2), sedative medications, and narcotics, between patients who were delirious for the majority of their ICU stay compared with patients who were not. Results of these comparisons were considered significant if p < 0.05. For these comparisons, the Bonferroni correction was used.
were purchased for each patient. Only the study investigators had access to the study data. The device manufacturer had no role in study design, data collection, statistics, or manuscript preparation.

RESULTS

Patients

Between March 1st and September 30th 2014, 62 patients were considered eligible for the study (Figure 1). Fifty-two of these patients met at least one exclusion criteria. There were no instances of refused or withdrawn consent. Baseline demographics and clinical features are shown in Table 1. All patients had a diagnosis of septic shock, were mechanically ventilated and were on vasoactive agents at the time of enrolment. The high severity of illness of this patient cohort is reflected in the mortality rate of 50%. The majority of patients (90%) had an underlying diagnosis of hypertension (a risk factor for the development of delirium6).

Recording of BtO2

The NIRS monitor used in this study has an internal sensor for detecting signal strength and it discontinued recording data once signal strength was compromised. All 10 patients had adequate signal strength at the beginning of the 72-hour recording; however, the signal strength universally degraded over the 72-hour period. This required repositioning of the sensors and often using additional adhesive, such as 3M Cavilon No Sting Barrier Film or 3M Tegaderm Film, to ensure good skin contact. In total, the NIRS monitor recorded 81% of the available data. There was variability from subject to subject, ranging from 45-98% of data captured per patient. The patient with the lowest number of recordings had monitoring suspended as they were taken out of the ICU in order to have a procedure performed. Another patient was transported out of the ICU with the monitor attached with backup battery power (four hours battery life) in order to have a CT head performed. The NIRS sensors did not interfere with the CT imaging. According to the device information, patients may rarely develop a rash to the adhesive used. No adverse events were documented in our patient cohort. The bedside nursing staff was contacted daily. Neither the NIRS monitor nor sensors interfered with their abilities to assess, and provide care for, their patients.

Correlation between BtO2 and patient variables

There was considerable intra- and inter-patient variability in the degree of correlation between BtO2 and hemodynamic variables measured, including SBP, DBP, MAP, and HR. Figure 2 shows how BtO2, HR, and MAP change over time in four sample patients. While one patient showed a direct correlation between increased heart rate and increased BtO2 (Figure 2A, B), another patient showed an inverse relationship (Figure 2, C,D). Throughout the recording period, patients would show variable relationships between BtO2 and their hemodynamic parameters. For example, the sample patient shown in Figure 2 (E) exhibits increases in BtO2 with increasing (white arrows), decreasing (black arrow), and constant (gray arrow) MAP. This significant

Table 1: Patient demographics and clinical features.

<table>
<thead>
<tr>
<th>Patient Demographics and Clinical Features</th>
<th>Total (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (mean, in years)</td>
<td>71 (range 43-85)</td>
</tr>
<tr>
<td>Male gender - n(%)</td>
<td>4 (40)</td>
</tr>
<tr>
<td>Medical history - n(%)</td>
<td></td>
</tr>
<tr>
<td>Hypertension:</td>
<td>9 (90)</td>
</tr>
<tr>
<td>Diabetes:</td>
<td>5 (50)</td>
</tr>
<tr>
<td>Cardiac disease:</td>
<td>3 (30)</td>
</tr>
<tr>
<td>Psychiatric illness:</td>
<td>2 (20)</td>
</tr>
<tr>
<td>Epilepsy</td>
<td>2 (20)</td>
</tr>
<tr>
<td>Admitting diagnosis - n(%):</td>
<td></td>
</tr>
<tr>
<td>Severe sepsis:</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Septic shock:</td>
<td>10 (100)</td>
</tr>
<tr>
<td>Source of infection - n(%)</td>
<td></td>
</tr>
<tr>
<td>Pneumonia:</td>
<td>3 (30)</td>
</tr>
<tr>
<td>Soft tissue:</td>
<td>3 (30)</td>
</tr>
<tr>
<td>Urological:</td>
<td>2 (20)</td>
</tr>
<tr>
<td>Other:*</td>
<td>2 (20)</td>
</tr>
<tr>
<td>At time of enrolment - n(%)</td>
<td></td>
</tr>
<tr>
<td>Mechanical ventilation:</td>
<td>10 (100)</td>
</tr>
<tr>
<td>Vasoactive agents:</td>
<td>10 (100)</td>
</tr>
<tr>
<td>ICU mortality - n(%)</td>
<td>5 (50)</td>
</tr>
<tr>
<td>ICU Length of Stay (mean, in days)</td>
<td>8.9 (range 2-30)</td>
</tr>
</tbody>
</table>

*other includes one spinal epidural abscess, and one patient with 3/4 SIRS (systemic inflammatory response syndrome) criteria, with presumed infection because no other likely etiology. n = number of patients; ICU = intensive care unit.
variability throughout the recording period is a possible explanation for the non-significant linear correlation seen in other patients (Figure 2F). Another sample patient however (C) had an inverse linear correlation (D) between these variables. In another sample patient, there are obvious concurrent increases in MAP and BtO2 (E, white arrows), but the same patient will demonstrate increasing BtO2 in response to falling MAP (black arrow), or an increase in BtO2 with a constant MAP (gray arrow). Because of this variability, there is a weak and non-significant linear correlation between these two variables (F). In the fourth sample patient, BtO2 increases over time as MAP decreases (G), resulting in a significant negative linear correlation (H).

Figure 2: BtO2 levels vary inconsistently with HR and MAP. Four sample patients are shown. Panel A shows the changes in BtO2 and HR over time. In this particular patient, there was a significant linear correlation (B) between increases in HR and increases in BtO2. Another patient however (C) had an inverse linear correlation (D) between these variables. In another sample patient, there are obvious concurrent increases in MAP and BtO2 (E, white arrows), but the same patient will demonstrate increasing BtO2 in response to falling MAP (black arrow), or an increase in BtO2 with a constant MAP (gray arrow). Because of this variability, there is a weak and non-significant linear correlation between these two variables (F). In the fourth sample patient, BtO2 increases over time as MAP decreases (G), resulting in a significant negative linear correlation (H).

septic shock is summarized in Figure 3. This figure is a correlation plot designed to visually represent a high volume of data, and part of the feasibility of this study is demonstrating efficient ways of representing large data series. Variability was also observed in the way BtO2 changed in response to pCO2, peripheral oxygen saturation (pO2), and pH (Figure 3). The R² values are shown in Table 2.
Brain tissue oxygen levels are lower in patients who experience more delirium

We performed delirium screening on a daily basis with the CAM-ICU. On the basis of this testing each patient was assigned to one of three groups daily, comatose (RASS $\leq -4$ or $\leq -5$; unable to assess with the CAM-ICU), delirious (CAM-ICU positive) and intact (CAM-ICU negative). Three patients were comatose (RASS $\leq -4$ or $\leq -5$) during their entire ICU stay. Of the remaining seven that could be assessed with the CAM-ICU, five were delirious for at least part of their ICU stay. Patients who spent more time neurologically intact (CAM-ICU negative) tended to have higher mean BtO$_2$ levels (Figure 4A). When we assessed the total number of recordings across the spectrum of BtO$_2$ levels (30-100%), patients who spent the majority of their ICU stay CAM-ICU negative ($n = 4$) had a higher frequency of BtO$_2$ levels above 70% than patients who spent the majority of their ICU stay CAM-ICU positive (Figure 4B). We compared the mean values of MAP, HR, SaO$_2$, and BtO$_2$ levels between patients who spent the majority ($\geq 50\%$) of ICU time either delirious or non-delirious. Only BtO$_2$ levels were statistically different between the two groups ($p < 0.0001$), with lower levels in patients who spent the majority of their ICU stay delirious (Figure 4C). Additionally, we recorded the sedative and analgesic infusions provided to patients during the 72-hour period of BtO$_2$ recording. There were no significant differences in the total dose of

Figure 3: Correlation plot provides visual representation for the correlation between BtO$_2$ and other hemodynamic/physiological parameters. Each cell represents the $R^2$ value for the correlation between BtO$_2$ and the clinical parameter in the column, for the individual patient in the row. If there is no ellipse, then the correlation coefficient is zero. The strength and direction of correlation are dually represented. The increasing strength is represented by the density of the colour as well as by narrowing radius of the ellipse. The direction of the correlation (positive or negative) is represented by the colour of the ellipse (blue = positive correlation; red = negative correlation), as well as its orientation (ellipses angled up and to the right represent positive correlations). The asterisk indicates significant linear correlations ($p < 0.05$). The grey rectangles for patients 1, 2, 4, and 8 indicate that insufficient values were available to calculate the correlation coefficient.
midazolam (Figure 4D), fentanyl (Figure 4E), or propofol
(Figure 4F) between patients that spent the majority of their ICU
stay delirious, versus those that spent the majority of their time
neurologically intact.

Relationship between BtO2 and hemoglobin concentration

In addition to heart rate, MAP, and peripheral oxygen
saturation, the concentration of hemoglobin is an important
determinant of oxygen delivery to tissues. Therefore, we assessed
whether there was a relationship between hemoglobin concen-
tration and BtO2. As shown in Figure 5, there was a trend
towards having a direct linear correlation between increasing
BtO2 levels and hemoglobin concentration; however, this did not
reach statistical significance ($p = 0.07$). While this graph again
highlights the fact that patients that spent the majority of their time
non-delirious (white circles) tended to have a higher BtO2, there
was no significant difference in the mean hemoglobin concentra-
tion between patients that were comatose, delirious, or intact
($p > 0.05$).

DISCUSSION

Feasibility and safety

This study screened 62 eligible patients with severe sepsis and
septic shock over a six-month period of time. As 52 of these
patients met at least one exclusion criteria, only 10 were recruited
into the study. Thus the recruitment rate was 1.7 patients/month.
This may seem low given our large 33-bed medical surgical ICU,
however, it is in keeping with other studies of critically ill patients.
Recruitment rates may vary, from less than one patient every two
months in large and complex multi-centre trials (e.g. The ARISE
Trial28), to two to three patients per month in smaller single centre
observational studies.29 Low rates of recruitment may be attrib-
uted to the lack of 24-hour availability of study coordinators, or
simply reflect the challenges of recruiting patients in a complex
critical care environment. In order to detect a moderate correlation
between average BtO2 and proportion of delirium days experi-
enced, 100 evaluable patients would be required to achieve
87% power at a 2-sided alpha $= 0.05$. In our pilot study, 30%
of patients were comatose for their entire ICU stay and could not
be screened for delirium. Therefore, future studies investigating
the relationship between BtO2 and delirium would need recruit-
ment of 150 patients. Furthermore, in light of the fact that the
majority of our patients were excluded because they were beyond
the 24-hour window, future studies should focus on earlier
identification of patients with severe sepsis and septic shock,
with particular emphasis on early recognition in the emergency
department.

With regards to data collection, ours is the first study to
demonstrate the feasibility of using NIRS to perform long-term
continuous recording of BtO2 in patients with septic shock.
The device captured most of the available data, did not interfere
with the care of the critically ill patient, and no adverse
events occurred. Throughout the course of the study in the ICU,
some factors were discovered which can interfere with NIRS
recordings. These factors include: patient transfer for various
procedures (e.g. magnetic resonance imaging), loss of battery
power on the cerebral oximeter, and ambient light interfering with
the cerebral oximeter acquiring a signal. However, these inter-
ferences can be quickly remedied by plugging in the oximeter
during patient transfer to restore power, reattaching the sensor
if it is disconnected for a medical procedure, and closing the
blinds in a patient’s room to help block ambient light from
degrading the NIRS signal. Furthermore, additional adhesives
were often used to keep the sensor in place as the original
adhesive degraded after the first 24 hours. This additional sensor

Table 2: Correlation between physiological parameters and brain tissue oxygenation for each individual patient.

<table>
<thead>
<tr>
<th>Patient number</th>
<th>SBP</th>
<th>DBP</th>
<th>MAP</th>
<th>HR</th>
<th>SaO2</th>
<th>pH</th>
<th>pO2</th>
<th>pCO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.07</td>
<td>0.01</td>
<td>0.05</td>
<td>0.08</td>
<td>0.11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.02</td>
<td>0.01</td>
<td>0.04</td>
<td>0.08</td>
<td>0.01</td>
<td>0.55</td>
<td>0.44</td>
<td>0.01</td>
</tr>
<tr>
<td>3</td>
<td>0.08</td>
<td>0.09</td>
<td>0.13*</td>
<td>0.07</td>
<td>0.11</td>
<td>0.41</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>4</td>
<td>0.01</td>
<td>0.08</td>
<td>0.04</td>
<td>0.07</td>
<td>0.11</td>
<td>0.10</td>
<td>0.12</td>
<td>0.83*</td>
</tr>
<tr>
<td>5</td>
<td>0.08</td>
<td>0.09</td>
<td>0.13*</td>
<td>0.13*</td>
<td>0.04</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>-0.04</td>
<td>-0.09</td>
<td>0.07</td>
<td>-0.36*</td>
<td>-0.34*</td>
<td>0.96*</td>
<td>0.44</td>
<td>-0.73*</td>
</tr>
<tr>
<td>7</td>
<td>0.03</td>
<td>0.04</td>
<td>0.07</td>
<td>0.08</td>
<td>0.43*</td>
<td>0.03</td>
<td>0.59*</td>
<td>0.01</td>
</tr>
<tr>
<td>8</td>
<td>-0.03</td>
<td>-0.22*</td>
<td>-0.19*</td>
<td>0.10</td>
<td>0.44*</td>
<td>0.13*</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.01</td>
<td>0.14*</td>
<td>0.05</td>
<td>0.06</td>
<td>0.14</td>
<td>0.22</td>
<td>0.24</td>
<td>0.01</td>
</tr>
<tr>
<td>10</td>
<td>0.15*</td>
<td>0.05</td>
<td>0.36*</td>
<td>0.05</td>
<td>0.14</td>
<td>0.59*</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>0.03</td>
<td>0.05</td>
<td>0.08</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Min</td>
<td>-0.04</td>
<td>-0.22</td>
<td>-0.19</td>
<td>-0.36</td>
<td>-0.34</td>
<td>-0.12</td>
<td>-0.22</td>
<td>-0.73</td>
</tr>
<tr>
<td>Max</td>
<td>0.15</td>
<td>0.14</td>
<td>0.13</td>
<td>0.60</td>
<td>0.43</td>
<td>0.96</td>
<td>0.59</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Grey shaded cells indicate insufficient values were available to calculate linear correlation coefficients.

$R^2 =$ linear correlation coefficients, BtO2 = brain tissue oxygenation levels, SBP = systolic blood pressure; DBP = diastolic blood pressure, MAP = mean arterial pressure, HR = heart rate, SaO2 = peripheral oxygen saturation, pO2 = partial pressure of oxygen, pCO2 = partial pressure of carbon dioxide.

* = $p < 0.05^2$. 
upkeep was minor and only took a couple minutes per patient. Additional length of upkeep was minor and not recorded since it did not greatly impact patient care or data collection. Despite these minor challenges, we were able to assess the relationship between BtO₂ and hemodynamic parameters, measurements of gas exchange (peripheral oxygenation pO₂, and pCO₂), as well as the development of delirium as an indicator of acute neurological dysfunction.

Figure 4: Patients that experience more delirium have lower levels of BtO₂. Patients were assessed daily for delirium with the CAM-ICU, and were categorized as either comatose (RASS −4, −5; unable to screen with CAM-ICU; black bars), CAM-ICU positive (delirious; grey bars), or CAM-ICU negative (intact; white bars). (A). The number of days spent in each condition is represented as a percentage of the total number of days in the ICU for each individual patient arranged in order of increasing mean levels of BtO₂ (B). Lower BtO₂ values were recorded more frequently in patients who screened positive for delirium during the majority of their ICU stay (grey area) compared to patients who were intact for the majority of their ICU stay (white area). (C). BtO₂ levels were significantly lower in patients experiencing delirium (grey bars) during the majority of their ICU stay when compared to intact patients (white bars). However, no differences were observed in MAP, HR, or SaO₂. Additionally, there were no significant differences in total dose of midazolam (D), fentanyl (E), or propofol (F) between patients who were delirious (grey bars) or intact (white bars) for the majority of their ICU stay.
Determinants of BtO2 in patients with septic shock

During the first 72 hours of critical illness, we demonstrated significant inter- and intra-individual variability in the way BtO2 varies with hemodynamic parameters, such as systolic blood pressure and heart rate, as well as with peripheral oxygenation and pCO2. In some patients, there was a positive correlation between SBP, MAP, and HR with BtO2. In other patients however, an inverse correlation was documented. The high degree of variability in the way BtO2 responds to changes in hemodynamics and oxygenation may significantly impair our ability to develop standardized algorithms to optimize BtO2, which exist for patients undergoing cardiac surgery. The variable manner in which BtO2 changes in response to fluctuations in hemodynamics may be a reflection of altered cerebral autoregulation in patients with severe sepsis and septic shock. Using transcranial doppler (TCD), Pfister and colleagues demonstrated altered cerebral vessel reactivity in patients experiencing delirium in the context of septic shock but not in patients that screened negative for delirium. Similarly, Pierrakos et al. used TCD to demonstrate increased cerebrovascular resistance in septic patients experiencing delirium, compared to septic, non-delirious patients. Other studies using TCD and NIRS to assess cerebral autoregulation in sepsis/septic shock have documented intact autoregulation, with the exception of extremes of blood pressure and pCO2; however, the authors of the study did not comment on whether or not the patients were delirious at the time of assessment. The considerable inter-individual variability in correlation between BtO2 and hemodynamics may also be due to changes in microvascular reactivity and endothelial dysfunction observed in patients with septic shock. However, this is beyond the resolution of NIRS technology.

Brain tissue oxygen levels and acute neurological dysfunction in patients with septic shock

Although the primary outcome of this study was feasibility, one of our secondary outcomes was to explore possible differences in hemodynamics and BtO2 among patients with septic shock who are experiencing acute neurological dysfunction. Our findings of significantly lower mean BtO2 levels in patients with delirium raises the interesting possibility that poor brain oxygen delivery in the first 72 hours after admission for septic shock may contribute to acute neurological dysfunction in these patients. Others have performed one hour of NIRS monitoring beginning 48 hours after ICU admission to assess BtO2 in patients with septic shock. They did not find differences in values between patients experiencing delirium and patients not experiencing delirium. This differs from the results of our small pilot study that demonstrated a significant difference in BtO2 between delirious and non-delirious patients. The lack of agreement in these findings likely reflects the small sample sizes, as well as significant methodological differences. Nevertheless, together with our data, these data provide a compelling rationale to further explore the relationship between BtO2 and delirium in a large prospective study. Another important limitation of NIRS technology is that it is only designed to record frontal lobe tissue oxygenation. Given the importance of the frontal lobes in attention and executive function, they are likely relevant to the clinical manifestations of delirium. This is supported by the fact that patients who experience a greater duration of delirium in the ICU exhibit a greater degree of frontal lobe atrophy on magnetic resonance imaging three months later.

CONCLUSIONS

Continuous, non-invasive recording of BtO2 with NIRS is feasible in patients with septic shock. This study will provide the protocols necessary for a larger prospective observational study to further examine the relationship between BtO2, physiological parameters, and acute neurological dysfunction.

ACKNOWLEDGMENTS

The authors thank our study coordinators, Ms. Jenna Podilchak and Ms. Suzy Fleury, for their assistance with getting consent, initiating the NIRS monitoring, and providing support for the bedside nursing staff and thank Dr. Andrew Day for his statistical expertise.

STATEMENT OF AUTHORSHIP

MW participated in data collection, data analysis, and drafting of the manuscript. AS participated in data collection and data analysis. DM participated in data analysis as well as preparing and editing the final draft of the manuscript. CF, DH and JM participated in the conceptualization and design of the study, as well as editing the final draft of the manuscript. JGB was the principal investigator and was responsible for design and implementation of the study, data collection and analysis, as well as writing and editing the final draft of the manuscript.
REFERENCES


