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Transcranial regional cerebral oxygen desaturation predicts delayed cerebral ischaemia and poor outcomes after subarachnoid haemorrhage: A correlational study

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Summary

Objectives—To examine the relationship between regional cerebral oxygen saturation (rSO₂), delayed cerebral ischaemia (DCI), and outcomes after aneurysmal subarachnoid haemorrhage (aSAH).

Research Methodology—Subjects ($n = 163$) with aSAH, age 21–75 years, and Fisher grade >1 were included in the study. Continuous rSO₂ monitoring was performed for 5–10 days after injury using near-infrared spectroscopy with sensors over the frontal/temporal cortex. rSO₂ < 50 indicated desaturation. DCI was defined as neurological deterioration due to impaired cerebral blood flow. Three- and 12-month functional outcomes were assessed by the modified Rankin scale (MRS) as good (0–3) and poor (4–6).

Results—DCI occurred in 57% of patients; of these 66% had rSO₂ < 50 . Overall, 56% had rSO₂ < 50 on either side, 21% and 16% had poor MRS at 3 and 12 months. Subjects with rSO₂ < 50 were 3.25 times more likely to have DCI compared to those with rSO₂ > 50 (OR 3.25, 95% CI 1.58–6.69), positive predictive value (PPV) = 70%. Subjects with rSO₂ < 50 were 2.7 times more likely to have poor 3-month MRS compared to those with rSO₂ > 50 (OR 2.7, 95% CI 1.1–7.2), PPV = 70%.

Conclusions—These results suggest that NIRS has the potential for detecting DCI after aSAH. This potential needs to be further explored in a larger prospective study.

Keywords

Cerebral oxygen; Delayed cerebral ischaemia; Subarachnoid Haemorrhage

Introduction

Continuous monitoring after aneurysmal subarachnoid haemorrhage (aSAH) is essential to detect complications (Mazzeo and Bullock, 2007). Several complications have been reported after aSAH, but delayed cerebral ischaemia (DCI) remains the primary target for interventions. DCI is associated with poor functional and cognitive outcomes, severe disability and higher mortality rate (Frontera et al., 2009; Springer et al., 2009). Early detection of DCI within the therapeutic window during which tissue can be recovered is key to improving outcomes and reducing mortality and can be best achieved through proper continuous monitoring. Because the brain requires a continuous supply of oxygenated blood, changes in blood flow can be quickly reflected by a decrease in the regional cerebral oxygen saturation (rSO_2).

Many models have been proposed to predict DCI (Carrera et al., 2009; Dankbaar et al., 2010; Hop et al., 1999). However, the ability of these predictive models to detect DCI at the bedside remains limited. There are several approaches to monitor DCI after aSAH. These include for example clinical examination to assess clinical deterioration, computerised tomography (CT) perfusion scan to assess cerebral blood flow and transcranial Doppler (TCD) to assess cerebral blood flow velocities. These approaches are typically utilised in an intermittent fashion and require the patient to leave the intensive care unit (ICU) or most importantly alert for symptoms after the damage has already occurred. Unlike these approaches, rSO_2 can be monitored continuously at the bedside, does not require the patient to leave the ICU, and may hold the potential for alerting to decreased cerebral oxygenation before symptoms develop. Thus, changes in rSO_2 may be utilised as an early warning sign for impending DCI. Therefore, examining the association between rSO_2 and DCI appears to be warranted. The purpose of this study was to examine the relationship between rSO_2 and DCI and functional outcomes post aSAH.

Methods

This analysis has utilised data collected for the parent study R01 (NR004339-10). The study was approved by the Institutional Review Board (IRB) at the University of Pittsburgh (REN11040212/IRB021039). The risk in the current study was minimal and was restricted to potential loss of confidentiality. All subjects have had study identification numbers and data for the current study were analysed after it was de-identified. During the consent procedure for the parent study, subjects were informed that their participation was completely voluntary and the decision whether to enrol in the study would not affect the standard of care they received. There was no exclusion based on gender, ethnicity or race.

Sample and setting

This longitudinal correlational study recruited 163 subjects with aSAH who were admitted to the University of Pittsburgh Medical Center's Neurovascular Intensive Care Unit (NICU) between May 1999 and January 2003. Subjects were enrolled in a National Institute of Health (NIH) funded study (R01 NR004339-10). Inclusion criteria were adults 21–75 years of age with ruptured cerebral aneurysm/s, Hunt and Hess score >2 and/or Fisher grade >1 and admission to NICU. Exclusion criteria were: preexisting chronic neurologic disease, and traumatic or mycotic aneurysm. Subjects were recruited within five days of the bleeding onset, after which in-hospital follow-up for 14 days (or until discharge) was performed. The diagnosis of the subarachnoid bleed was confirmed using CT scan, while the diagnosis of cerebral aneurysm was made using cerebral angiography.

Regional cerebral oxygen saturation

Noninvasive continuous bilateral rSO₂ monitoring was performed 5–10 days post-bleeding using near-infrared spectroscopy (NIRS) (INVOS4100, Somanetics Corp.) positioned over the frontal/temporal cortex. NIRS is a well-known noninvasive optical monitoring technique that utilises the changes in oxyhaemoglobin and deoxyhaemoglobin to estimate the oxygen saturation in a living brain tissue (Hillman, 2007). This technique uses near-infrared light for better penetration of the tissue around the brain as well as the brain tissue itself. There are several advantages as well as limitations of this technique. NIRS is relatively inexpensive, can provide continuous data streams, does not require high level of expertise to implement on patients, and can be done at the bedside without moving critically ill patients to the radiology department. However, NIRS is only effective if the near-infrared light penetrates the tissue. Therefore, factors that impede this penetration (such as scalp hair and light scattering) may limit the use of this technology. Despite these limitations, rSO₂ measured by NIRS has potential for use in critically ill patients. Brawanski et al. have investigated the correlation between rSO₂ (using NIRS) and local oxygen pressure in the brain white matter (tip) and found significant correlation despite the different methodologies utilised in each technology (Brawanski et al., 2002). Brain tissue oxygen tension (PtO₂) uses a microcatheter inserted in the brain tissue to assess cerebral oxygenation. Jugular bulb oximetry (SjvO₂) assesses cerebral blood flow-metabolism coupling (Rohlwink and Figaji, 2010). The correlation between rSO₂ using NIRS and both PtO₂ and SjvO₂ is poor and not entirely significant (Buunk et al., 1998; Tyree et al., 2009). However, rSO₂ measured using frontal NIRS oximetry is significantly related to the cerebral blood flow values assessed using CT perfusion scans (Taussky et al., 2012). Therefore, despite the weak correlation between NIRS-measured rSO₂ and PtO₂ and SjvO₂, proper use of NIRS technology still has potential for clinical use in critically ill patients.

In this study, an rSO₂ value of <50 for at least 30 minutes was used to indicate cerebral desaturation. Patients who had an rSO₂ value of <50 at either side at least one time during the observation period were considered as having insufficient oxygenation. rSO₂ values that were judged to be due to artefacts (device disconnection) were excluded from the analysis.

Delayed cerebral ischaemia

The definition of DCI has been used in an inconsistent fashion in research. The Neurocritical Care Society has recently published new guidelines for managing patient with aSAH in which DCI was re-defined based on the consensus of experts in the field (Diringer et al., 2011). Thus, we decided to examine these data using the new definition of DCI.

DCI was defined as the presence of focal or global neurological deterioration, not attributable to rebleeding, seizures, hydrocephalus, fever or cerebral oedema, accompanied by the evidence of impaired cerebral blood flow. Neurologic deterioration criteria were as follows: a) deterioration in level of consciousness measured by Glasgow coma scale, b) new focal neurologic deficit, c) deterioration in pupillary reaction d) deterioration in the NIH Stroke Scale. Cerebral blood flow was indirectly assessed using the following measures: transcranial Doppler (TCD), CT or CT perfusion scan and/or digital subtraction angiography. Cerebral blood flow assessments that were performed within 12 hours (before, after or both) window of the observed neurologic deterioration were considered in the DCI criteria. Indications for impaired cerebral blood flow using TCD included mean middle cerebral artery velocity >120 ml/second, systolic middle cerebral artery velocity >200 ml/second or Lindegaard ratio >3.0 . Cerebral ischaemia, infarction and cerebral blood flow asymmetry were evaluated on head CT scans/CT perfusion scans that were reviewed independently by a radiologist. Cerebral angiography was independently performed and evaluated by a neurosurgeon with narrowing $>25\%$ indicating significant vasospasm. The diagnosis of DCI was made when a subject had both neurologic deterioration and one or more indicator of impaired cerebral blood flow.

Outcomes

Three and 12 month functional outcomes and mortality were assessed by using the modified Rankin scale (MRS). MRS incorporates mental and physical adaptations to the deficits resulting from neurologic injury using a scale from 0 (no symptoms at all) to 6 (death). MRS was categorised as good (0–3) and poor (4–6).

Statistical analyses

Comparison of clinical differences between subjects with $rSO_2 < 50$ and those with $rSO_2 > 50$ was performed using Exact test, Mann–Whitney U test and Student's t -test. When the results of nonparametric tests were consistent with those from parametric tests, parametric test statistics were reported for simpler interpretation. Univariable and multivariable binomial logistic regression was used to test the relationship between 1) rSO_2 and DCI and 2) rSO_2 and MRS. The conventional 0.05 α level was used to indicate significance. Multivariable analyses were conducted controlling for age, bleeding severity (Fisher grade) and aneurysm repair method (endovascular coiling vs. surgical clipping).

Results

The clinical and demographic characteristics of the sample are shown in Table 1. The subjects were middle age adults, predominantly Caucasian and female. The majority of the subjects had Hunt and Hess grade of 2–3 and Fisher grade 3 and mainly underwent surgical

clipping. The proportions of the demographic and clinical characteristics were similar in the DCI group and the non-DCI group.

Values of rSO_2 were similar on both sides. On the left side, the minimum values ranged from 30 to 65, while the maximum values ranged from 65 to 99. The mean ranged from 47.1 to 82.8 while the standard deviation ranged from 2.7 to 21.0. On the right side, the minimum values ranged from 30 to 69, while the maximum values ranged from 51 to 99. The mean ranged from 40.1 to 80.2 while the standard deviation ranged from 1.3 to 28.9.

Of all subjects, 57% had DCI, 56% had $rSO_2 < 50$, 21% had poor MRS at 3 months and 17% had poor MRS at 12 months. DCI status could not be determined for 10 (6%) subjects because of inability to assess neurological deterioration due to coma or sedation. Two (1.2%) subjects were missing rSO_2 data, 22 (13%) subjects were missing 3-month MRS and 25 (15%) subjects were missing data on 12-month MRS as lost to follow-up.

Table 2 shows the clinical differences between subjects with $rSO_2 < 50$ and those with $rSO_2 > 50$. Significant differences were found in age, admission Glasgow coma scale, NIH stroke scale, and Fisher grade. Subjects with $rSO_2 < 50$ were significantly older, had lower Glasgow coma scale, higher NIH stroke scale and twice the proportion of Fisher grade 4 compared to those with $rSO_2 > 50$. rSO_2 was significantly associated with DCI. In univariable analysis, subjects with $rSO_2 < 50$ were 3.2 times more likely to have DCI compared to those with $rSO_2 > 50$ (OR 3.2, 95% CI 1.6–6.3) with a positive predictive value (PPV) of 73% and a negative predictive value (NPV) of 54%. After controlling for age, Fisher grade, and aneurysm repair method, $rSO_2 < 50$ remained an independent predictor of DCI (OR 3.25, 95% CI 1.58–6.69). rSO_2 was also associated with functional outcomes. Subjects with $rSO_2 < 50$ were 3.6 times more likely to have poor 3-month MRS compared to those with $rSO_2 > 50$ (OR 3.6, 95% CI 1.4–8.9). In multivariable analysis, rSO_2 remained an independent predictor of poor 3-month MRS (OR 2.72, 95% CI 1.02–7.20), Table 3. rSO_2 was not associated with 12-month MRS in both univariable and multivariable analyses.

Discussion

The main finding of this study was that rSO_2 is related to DCI and 3-month poor functional outcomes measured by MRS. Although NIRS has been utilised previously in patients with aSAH to assess autoregulation and to predict vasospasm (Budohoski et al., 2012; Yokose et al., 2010), this is the first study to report the relationship between rSO_2 and DCI in a large data-based analysis. Our findings suggest that NIRS can support current bedside monitoring of cerebral ischaemia after aSAH.

NIRS has been previously utilised in several ways in patients with aSAH. Budohoski and colleagues have used NIRS to assess cerebral autoregulation failure. They concluded that impaired cerebral autoregulation was associated with DCI (Budohoski et al., 2012; Czosnyka, 2012). Others have compared NIRS-based autoregulation index with cerebral perfusion pressure/transcranial Doppler index (Mx). They reported significant correlation between the two suggesting that NIRS can be reliably used to assess autoregulation after aSAH (Zweifel et al., 2010). NIRS was also used to assess regional cerebral oxygenation

along with diffuse correlation spectroscopy to assess cerebral blood flow. Potentials for improving cerebral haemodynamic monitoring when both are assessed simultaneously were reported (Kim et al., 2010). Similarly, the use of NIRS has been validated with cerebral blood flow measured through perfusion CT scan. A significant linear correlation between rSO_2 measured through frontal NIRS and cerebral blood flow was found (Taussky et al., 2012).

NIRS has also been utilised as a monitoring tool in the neurocritical care setting as well as for neurodiagnostic purposes. Maslehaty and colleagues have used NIRS to monitor rSO_2 for 12 days after aSAH. They included nine patients with aSAH, seven of whom did not experience vasospasm. The authors reported a decline in rSO_2 that preceded new ischaemic stroke in one of the remaining patients (Maslehaty et al., 2012). Others have used NIRS during endovascular neuroradiologic procedures such as aneurysm and AVM embolisation and diagnostic angiography (Mazzeo et al., 2012). In this setting, the authors reported that greater change in rSO_2 values was observed with more invasive procedures. Furthermore, changes in rSO_2 values helped to diagnose and manage two procedure-related adverse events. Other studies have suggested that NIRS can be useful in neurocritical care setting by providing more information to the clinicians, helping to evaluate therapy that aims to improve cerebral oxygenation and thus reducing secondary complications (Mazzeo and Bullock, 2007). This was tested in a case study by Mutoh and colleagues, who used NIRS to monitor rSO_2 during the use of intra-arterial vasodilators to treat vasospasm-related DCI after aSAH. Decreased rSO_2 was reported in the affected territories and rSO_2 values were improved after the administration of intra-arterial vasodilators (Mutoh et al., 2011). Likewise, Yokose and colleagues have used NIRS to investigate whether rSO_2 can be used to detect vasospasm. In seven patients with poor grade aSAH, three had sudden decrease in rSO_2 after which cerebral angiography revealed severe vasospasm (Yokose et al., 2010, Sakatani, 2010).

NIRS was also used outside the neurocritical care setting to monitor cerebral oxygenation in patients undergoing aortic surgery. It was found that decreased rSO_2 in these patients was strongly associated with neurological deteriorations. Values below 55 needed immediate attention according to the authors (Orihashi et al., 2004).

Findings from the current study and the literature support the need for the use of cerebral oximetry monitoring at the bedside. However, there are several limitations of NIRS that need to be recognised. Hair follicles affect rSO_2 values measured by NIRS. Therefore, it is more reliable when used on the forehead. Evaluating rSO_2 in the posterior circulation is therefore difficult (Mazzeo et al., 2012). Further, since haemoglobin absorbs the infrared light, blood in the subarachnoid or subdural space can also affect rSO_2 values.

Despite these limitations, noninvasive cerebral oxygen monitoring after aSAH has several advantages. It can be continuously monitored, thus providing a dynamic type of monitoring that allows tracking changes in cerebral oxygenation in real-time and helping to detect these change at the bedside. Other methods used to assess cerebral blood flow such as xenon-enhanced CT scan, PET scan, and perfusion-weighted MRI provide static/periodic monitoring. These scans are usually performed after changes in neurological status are

observed; thus detection of decrease in cerebral blood flow is delayed and tissue damage may not be reversible. Furthermore, moving patients from the intensive care unit (ICU) to the radiology department has known risk for cardiorespiratory instability. NIRS technology and testing do not require the patient to be transferred outside the ICU. The use of the NIRS has been validated in a sample of a patient with neurological injury including aSAH (Taussky et al., 2012). Therefore, despite the limitations, NIRS is a valid tool that needs to be utilised optimally in the neurocritical care setting.

This study has some limitations. Most of the subjects underwent surgical aneurysm clipping and had external ventricular drain, which may limit the generalisability of this study. Further, we did not correlate rSO₂ with radiologic evidence of ischaemia. However, DCI is diagnosed based on clinical deterioration after excluding causes other than impaired cerebral blood flow such as rebleeding, hydrocephalus, seizure, and cerebral oedema. Patients were recruited between 1999 and 2003; therefore, changes in the standard of care in the past years may have affected the findings. However, findings from this study are consistent with the current literature.

Conclusions

Assessing neurological deterioration through physical examination is subjective and is performed intermittently. Moving patients to radiology department increases the risk for complications. The objective nature of NIRS and the ability to continuously and noninvasively assess rSO₂ make cerebral oximetry a valuable tool for the clinical detection of DCI. Findings from this study suggest that NIRS has potentials for use in the neurocritical care setting. However, these potentials need to be further explored in a larger prospective study that determines whether the monitoring of rSO₂ using NIRS can detect DCI in a prospective sample.

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Implications for Clinical Practice

- $rSO_2 < 50$ is an independent marker of DCI with a substantial PPV that can potentially be used to detect DCI at the bedside.
- The objective nature of NIRS and the ability to continuously and noninvasively assess rSO_2 make cerebral oximetry a highly valuable tool for the clinical detection of DCI.
- Patients with lower Glasgow coma scale score, higher NIH stroke scale score and higher bleeding grades, and older patients have greater risk for cerebral oxygen desaturation after aSAH.

Table 1Subjects characteristics ($n = 164$).

Characteristics	Overall $n = 164$	DCI present $n = 94$	DCI absent $n = 60$
Age [median (range)]	54(22–75)	54(22–75)	53(25–75)
Female (n)%	(118)72%	(67)71%	(42)70%
White	(151)92%	(86)92%	(56)93%
Admission Hunt and Hess			
Grade 1	(25)15%	(14)15%	(10)17%
Grade 2	(51)31%	(31)33%	(19)32%
Grade 3	(50)31%	(35)25%	(24)40%
Grade 4	(25)15%	(16)17%	(4)7%
Grade 5	(13)8%	(10)11%	(3)5%
Fisher grade			
Grade 2	(35)21%	(15)15%	(20)33%
Grade 3	(102)62%	(61)65%	(32)53%
Grade 4	(27)17%	(19)20%	(8)13%
Aneurysm treatment			
Surgical clipping	(106)65%	(65)69%	(36)60%
Endovascular coiling	(57)35%	(28)30%	(24)40%

Table 2Comparison of clinical characteristics between subjects with $\text{rSO}_2 > 50$ and < 50 ($n = 162$).

Variable	$\text{rSO}_2 > 50$ $n = 71$	$\text{rSO}_2 < 50$ $n = 91$	p
^a Age (M $\pm$ SD)	50.8 $\pm$ 13.3	55.7 $\pm$ 11.6	0.013
^a Admission Glasgow coma scale (M $\pm$ SD)	12.7 $\pm$ 3.6	10.8 $\pm$ 4.5	0.004
^a NIH Stroke Scale (M $\pm$ SD) ($n = 155$)	4.6 $\pm$ 6.5	7.3 $\pm$ 7.3	0.016
Fisher			0.020
Grade 2	(20)28.2%	(15)16.5%	
Grade 3	(44)62%	(56)61.5%	
Grade 4	(7)9.9%	(20)22.0%	
Aneurysm site			0.161
Anterior circulation	(65)91.5%	(76)83.5%	
Posterior circulation	(6)8.5%	(15)16.5%	
Aneurysm treatment ($n = 161$)			
Surgical clipping	(48)67.6%	(57)63.3%	0.619
Endovascular coiling	(23)32.4%	(33)36.7%	

^a Student's t -test results were consistent with Mann–Whitney U .

Table 3

Multivariable logistic regression for DCI and MRS.

Variables	DCI (n = 151) PPV = 70% NPV = 63%			3-month MRS (n=139) PPV = 70% NPV = 80%			12-month MRS (n = 136) PPV = 33% NPV = 81%		
	OR	95%CI	p	OR	95%CI	p	OR	95%CI	p
rsO ₂ <50	3.25	1.58–6.69	0.01	2.72	1.02–7.20	0.04	1.74	.65–4.69	0.27
Age	0.98	.95–1.01	0.16	1.06	1.02–1.11	0.01	1.05	1.01–1.09	0.03
Fisher grade			0.04			0.17			0.24
Grade 2 ^a									
Grade 3	3.06	1.24–7.56	0.02	1.98	0.49–8.00	0.34	1.04	0.25–4.23	0.96
Grade 4	3.05	.93–10.00	0.07	4.30	.09–21.10	0.07	2.52	0.53–11.94	0.25
Aneurysm coiling	0.72	.34–1.52	0.39	0.59	0.23–1.48	0.26	1.46	0.58–3.66	0.42

PPV; positive predictive value; NPV; negative predictive value.

^aReference category.