NIRS monitoring of brain and spinal cord – detection of adverse intraoperative events

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Abstract. Near infrared spectroscopy (NIRS) monitors changes in oxygenated haemoglobin (HbO₂), and redox status of cytochrome_{aa3} (cyt) continuously and non-invasively in living tissue. We present examples where clinically relevant changes in HbO₂ and/or cyt were detected in real time, allowing intervention to avert potentially harmful hypoxic-ischaemic damage to the brain and/or spinal cord. *Brain monitoring:* In children undergoing surgery on cardiopulmonary bypass, observations include that: atrial fibrillation (cardiac arrhythmia) lowered cerebral HbO₂ concentration; concealed haemorrhage decreased cerebral HbO₂ concentration; inadequate level of anaesthetic resulted in spikes of changes in volume with interventions such as suturing; circulatory arrest reduced brain HbO₂ and cyt redox status; and bypass pump problems compromised cerebral blood flow. *Spinal cord monitoring:* In the experimental animal, we observed that NIRS detected ischaemic change immediately following aortic compression, spinal column distraction (instrumentation to separate the vertebrae), and hypoxia. In an infant requiring release of a congenitally tethered spinal cord, we observed that traction on the spinal cord of the infant resulted in decreased total haemoglobin concentration. *Summary:* NIRS brain monitoring probably represents the “standard of care” during cardiac surgery because adverse events can be detected and quantified. Similarly, spinal cord monitoring could reduce ischaemic spinal cord damage in spinal cord surgery and aortic aneurysm repair.

1. Introduction

Cardiac surgery, spinal surgery and aortic aneurysm repair are associated with high rates of neurologic damage [8,10,18,20,29]. Much of this damage occurs because of hypoxic ischaemic injury, which results in an imbalance between neuronal energy supply and demand [4]. Near infrared spectroscopy (NIRS) is a completely non-invasive continuous monitoring technique that measures absolute changes in the concentrations of three clinically relevant chromophores that absorb light in the near infrared region. These chromophores are oxy- and deoxy-haemoglobin (HbO₂ and Hb, respectively) and the oxidized form of cytochrome_{aa3} (cyt) [3,13,21], all of which provide measures of tissue oxygenation. Cytochrome_{aa3}, embedded in the wall of the mitochondria within the cells, is the terminal enzyme in the electron transfer chain.

NIRS monitoring of the brain and spinal cord makes it possible to identify the onset of potentially remediable adverse events in real time. Brain monitoring with NIRS is already being called for as the standard of care during cardiopulmonary bypass surgery [12,23] and observations that ischaemic damage can also be detected in the spinal cord [19] may lead to its routine use during other types of surgery where there is the potential for oxygenation of the spinal cord to be adversely affected.

We present examples of intraoperative events, identified during NIRS monitoring, that had the potential to adversely effect brain or spinal cord function if they had not been identified in real time and remedied promptly.

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2. Methods

2.1. Equipment

Our team uses either the Hamamatsu NIRO 500 or NIRO 300 (Hamamatsu Photonics, Japan), commercially available near infrared spectroscopy units that emit light at four wave lengths (777, 828, 848, and 910 nm) from laser diodes and direct them into the tissue through a fibre-optic bundle. The terminals of the fibre-optic bundles, termed “optodes”, are prisms in the NIRO 500. In the NIRO 300, the transmitting optode is a prism and the receiving optode is a photodiode.

2.2. Brain monitoring during cardiac surgery

All studies had the approval of the institutional Clinical Research Ethics Board and informed consent was obtained. NIRS monitoring was initiated in the operating room following induction of anaesthesia. The method used was similar to that described by other investigators [1,11,16]. The optodes were positioned 30 mm apart, laterally over the frontal region to avoid potential interference from the sagittal sinus and temporalis muscle. Optodes were fixed to the scalp with elastic tape. An opaque bonnet excluded background light. In addition to NIRS, temperature (nasopharyngeal and rectal), 2-lead EEG, central venous pressure, end tidal CO₂, and blood pressure were monitored continuously throughout the procedure.

2.3. Spinal cord monitoring

Animal studies were approved by the Animal Care Committee. Animals were placed in a prone position, and the posterior spine exposed. Optodes were sutured in place in one of two configurations: over the T9 laminae and directed towards the spinal cord (interoptode spacing approximately 18 mm); or on the spinous processes of T9 and T10 (interoptode spacing initially 25 mm). A third configuration evaluated the situation with the optodes inserted into the spinal canal at the level of T9 and placed directly on either side of the spinal cord a fixed distance (6 to 10 mm) apart. Distraction of the spinal column was achieved through a T9 thoracotomy with the animal on its right side. The interoptode distance was measured with each distraction and on release. NIRS monitoring was continuous throughout the procedure. At data analysis, calculations were corrected for changes in the inter-optode distance.

For the infant studied during surgery, Clinical Research Ethics Board approval and parental informed consent were obtained. With the infant prone, the optodes were taped on the skin, with the optodes in line over the spinous processes cephalad to the surgical field. Monitoring was continuous throughout the procedure.

3. Results

Brain monitoring during cardiac surgery

- atrial fibrillation (cardiac arrhythmia) lowered cerebral HbO₂ concentration;
- concealed haemorrhage had a similar but more pronounced effect on cerebral HbO₂ (Fig. 1);
- inadequate level of anaesthetic resulted in spikes of changes in volume with interventions such as suturing (Fig. 2);

Fig. 1. Concealed bleeding in the thoracic cavity during cardiopulmonary bypass surgery observed via a change in cerebral haemoglobin concentration. This graph shows a decrease in both oxygenated and deoxygenated haemoglobin, and therefore a decrease in total blood volume.

Fig. 2. Anaesthetic level too low, resulting in transient cerebral oxygenation changes during suturing (dotted box indicates period of suturing), followed by a protracted period for return to baseline.

- circulatory arrest reduces brain HbO₂ and cyt activity (Fig. 3);
- cardiopulmonary bypass pump problems (air lock in tubing, kinked cannula, inadequate pump flow rate) compromise cerebral blood flow (Fig. 4).

4. Spinal cord monitoring

- in the experimental animal, spinal cord monitoring with NIRS indicated ischaemic change immediately with aortic compression, spinal column distraction (instrumentation to separate the vertebrae), and hypoxia (Fig. 5);
- signals were comparable on cord, on lamina, and on skin;

Fig. 3. Total circulatory arrest (period outlined by the box), showing equal and opposite changes in cerebral oxy- and deoxy-haemoglobin (indicating no change in total blood volume), with rapid recovery and some transitory increase in total blood volume on reinstatement of circulation.

Fig. 4. Loss of cardiopulmonary bypass pump pressure (period outlined by the box) resulted in decreased cerebral oxygenated haemoglobin concentration, with little change in deoxygenated haemoglobin, indicating an overall decrease in cerebral blood volume.

- dual site sampling is possible – either brain and spinal cord; or above and below a specific area of interest in the spinal cord;
- traction on the spinal cord during release of a congenitally-tethered cord in an infant resulted in decreased total haemoglobin concentration (Fig. 6).

5. Discussion

Our observations indicate that a number of significant intraoperative events capable of inducing significant hypoxia and or ischaemia can be detected with near infrared spectroscopic monitoring. Importantly, the information that results is available in real time and is quantifiable in terms of overall magnitude and duration. The monitoring provides the surgeons and anaesthetists with opportunities to intervene, and to know whether their action has or has not been effective. Clearly, if NIRS monitoring enables rapid and effective resolution of a detected problem, the probability is that the risk of short or long term neurological damage is decreased.

Fig. 5. Three periods (outlined by boxes) of spinal cord distraction (Moss Miami rods), with data corrected for change in interoptode spacing, showing equal and opposite changes in spinal oxy- and deoxy-haemoglobin with little or no change in total blood volume (indicative of ischaemia) during each event, and a cumulative increase in total blood volume over time.

Fig. 6. Traction on the spinal cord during release of tethered spinal cord resulted in a decrease in spinal oxygenated haemoglobin concentration.

During cardiac surgery, the circulation of blood is provided mechanically by a cardiopulmonary bypass pump that delivers non-pulsatile flow, and there may be periods of actual circulatory arrest. Even with the protection of whole body hypothermia to decrease cerebral oxygen demand, the brain is at risk. Similarly, during spinal and aortic surgery, the spinal cord blood flow is vulnerable, because of the risk of ischaemia and emboli. Monitoring techniques such as electroencephalography (EEG), somatosensory evoked potentials (SSEPs) and motor evoked potentials (MEPs) have been used to try to identify brain and/or spinal cord compromise within the time frame that would allow the surgeon to address the cause of the compromise [22,25]. However, no current electrodiagnostic method can identify vascular compro-

mise until neurologic function has been affected, which usually means that by the time the problem is identified, no remedial action is in fact possible.

NIRS monitoring can detect neuronal hypoxia in the brain prior to irreversible impairment of cellular metabolism, and can detect recovery during re-institution of circulation *before* the return of normal EEG activity [14]. Thus, NIRS monitoring provides a unique window of opportunity to detect the onset of sub-optimal oxygenation from a variety of causes in real time, and can effectively quantify the extent and duration of the adverse event, and indicate resolution when an intervention has been successful.

Although NIRS only detects a change from baseline, rather than an absolute value, the magnitude of change extends across a very obvious range. It is therefore possible to differentiate between small degrees of change that are of little consequence in terms of morbidity and overtly-extreme events with sudden or prolonged deterioration (predictive of non-survival), and identify moderate changes that provide the opportunity for investigation and intervention.

The development of NIRS monitoring, in our hands and with others, has progressed through various stages, exemplified here. Several reports published data from NIRS during cardiac bypass in adults, children and neonates. Although there were important differences in the observations, over the evolution of intraoperative monitoring with NIRS, its potential has been emphasized. Tamura [27], Greely [11] and Kurth [15] looked at Hb, HbO₂ and oxygen utilization; Fallon and Roberts reported the feasibility of measuring blood flow [7].

Initially, we identified large-scale blood flow issues, such as haemorrhage and pump problems. We were then able to identify more subtle physiological changes, such as those associated with reduced cardiac output due to atrial fibrillation (when the atrial component of heart's pumping action is missing). We found that this was readily detected, indicating that changes in flow within the physiological range were evident.

The next logical step was monitoring physiological function in the brain. Usually one would not expect changes in blood flow within the physiological range to have a measurable effect on brain metabolism. However, because there is an accumulating body of evidence to suggest that irreversible brain cell damage occurs at the level of the mitochondria [4], the ability of NIRS to monitor changes in cyt is exciting, and clinically valuable. DuPlessis [6], Skov [26], and our team [17] have looked at trends in cyt status as a means of evaluating brain metabolism. Work remains to be done in this area to understand the implications of the changes seen during monitoring on post-operative brain function, but an improvement in neurological morbidity is likely.

Intraoperative NIRS monitoring is now being called for as a standard of care for cardiac surgery [23], which we would endorse. Now that monitoring the spinal cord is also feasible, we would advocate that NIRS monitoring be extended to aortic aneurysm repair and some spinal operative procedures. Furthermore, others have used NIRS to monitor other organs, such as the liver for viability for transplant [5,24], the splanchnic bed for adequacy of recovery from hypovolemic shock [2,9], and the peripheral vascular beds for assessment of low blood pressure and anaemia in pre-term infants [28,30]. The intraoperative role of NIRS continues to be explored.

6. Summary

In cardiac surgery, NIRS monitoring is being called for as a standard of care. NIRS monitoring of the spine during spinal surgery or aortic aneurysm repair could dramatically reduce the incidence of spinal cord damage. The utility of NIRS continues to be explored.

Acknowledgements

Hospital for Sick Children (Toronto), Heart and Stroke Foundation of Canada, BC Research Foundation, and Children's Telethon have supported our work with NIRS.

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