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A Proposed Algorithm for the Intraoperative Use of Cerebral Near-Infrared Spectroscopy

André Denault, MD, FRCPC, ABIM-CCM, Alain Deschamps, MD, FRCPC, PhD, and John M. Murkin, MD, FRCPC

Near-infrared spectroscopy (NIRS) is a technique that can be used as a noninvasive and continuous monitor of the balance between cerebral oxygen delivery and consumption. The authors develop and propose an algorithm for the use of NIRS based on optimizing factors that can affect cerebral oxygen supply/demand. These factors are the position of the vascular cannula, perfusion pressure, arterial oxygen content, partial pressure of carbon dioxide, haemoglobin, cardiac output, and the cerebral metabolic rate of oxygen. Dissemination of a useful treatment algorithm is the primary purpose of this article. Further multicenter studies are necessary to confirm the benefits and cost-effectiveness of this promising monitoring modality.

Keywords: near-infrared spectroscopy; brain oximetry; neurological monitoring; cardiopulmonary bypass

Near-infrared spectroscopy (NIRS) is a technique that has been employed since the mid-1970s and can be used as a noninvasive and continuous monitor of the balance between cerebral oxygen delivery and consumption. This monitor is now being evaluated in a variety of different clinical areas such as neurology, neurosurgery, traumatology, vascular surgery, and adult and pediatric cardiac surgery. Despite various physiological applications, NIRS has been used mainly to detect and correct intraoperative cerebral desaturations — although the prognostic value of these desaturations, the specific thresholds requiring intervention, and the clinical impact of this type of monitoring is still debated.

NIRS provides a noninvasive measure of local tissue perfusion that can be used during nonpulsatile flow conditions such as cardiopulmonary bypass (CPB) or cardiac arrest. In 2 recent randomized trials, cerebral oximetry monitoring has been associated with shorter recovery room and hospital stay in noncardiac surgery and with a decrease in major organ dysfunction and in intensive care length of stay after cardiac surgery, thus providing rationale for its use.

NIRS Technology

NIRS technology, typified by the commercially available INVOS device (Somanetics, Troy, MI), is based on the principle that each tissue substance has a characteristic light absorbance. In the near-infrared wavelengths range, hemoglobin and cytochrome c oxidase, also known as the enzyme cytochrome aa3, are the main chromophores (light-absorbing substances at a specific frequency). Two adhesive patches attached to the forehead contain both the light sources and receivers, light-emitting diodes (LED) providing 2 continuous wavelengths of near-infrared light at 730 and 810 nm. The 730 nm wavelength measures the oxygenated/deoxygenated hemoglobin ratio; 810 nm is the frequency of the isobestic point (crossover point of
oxygenated/deoxygenated hemoglobin) and gives an
index of total light transmission where the arithmetic
difference between reflected signal strength is a meas-
ure of total tissue oxygenation. An important consid-
eration is the differential spacing of the 2 receiving
optodes, located at 3 and 4 cm laterally from the light
source. Because there is a relationship between the
depth of tissue penetration and the angle of incidence
of reflected light, the differential spacing of the receiv-
ing optodes facilitates the use of subtraction algo-

Figure 1. Operating principles of the use of near-infrared spectroscopy. (A) The electrodes are positioned in the forehead. (B) Signals
from both hemispheres are transmitted to a display. (C) The signals are coming from an optode that has 1 transmitter and 2 receptors.
The signal originating from the proximal receptors are subtracted from the distal ones. Therefore, only information from the deeper part
of the brain is displayed. (D) On the screen, the large number indicates the ongoing brain oximetry values and the small number the baseline
value obtained at the beginning of the recording from both the right (R) and the left (L) hemisphere.

NIRS Clinical Algorithm

One of the most important requirements in the moni-
toring of cerebral saturation is the elaboration of a
clinical algorithm to correct decrease in cerebral satu-
ration values. We have introduced the use of NIRS
into clinical practice at the London Health Science
Center in 2000 and at the Montreal Heart Institution
in June 2002, reviewed the evidence for its use in the
literature,7,14,15 performed studies,11,16 and have been
able to develop an algorithm in the use of NIRS. This
algorithm is based on optimizing those factors that can
affect cerebral oxygen supply/demand such as perfu-
sion pressure, cardiac output, arterial oxygen content,
partial pressure of carbon dioxide (PaCO₂), and cere-
bral metabolic rate. Other factors such as blood pH,
body temperature, the presence of abnormal hemoglobin, or changes in the level of 2,3-diphosphoglycerate can modify hemoglobin affinity for oxygen, thus influencing the amount of oxygen released to the tissues. Furthermore, brain oxygen consumption or the cerebral metabolic rate of oxygen (CMRO₂) is influenced by factors such as activation status, brain temperature, anesthetic agents, and pulsatile or laminar perfusion. Finally, some studies have also reported a relationship between regional cerebral oxygen saturation (rSO₂) and cardiac function. Therefore, the proposed algorithm is based on these considerations. Several examples illustrating the use of NIRS in the operating room environment are also presented.

The algorithm (Figure 2) explains the methodology through which we are currently using NIRS in the perioperative environment. This approach, based on our experience, goes through several comprehensive and logical steps to help correct decreases in cerebral saturation values. Ideally, baseline values should be obtained when the patient is awake, resting comfortably with O₂ supplementation. We define abnormal rSO₂ as a 20% bilateral or unilateral reduction from baseline values or an absolute decrease below 50%.

**Step 1: Rule Out Mechanical Obstruction**

**Arterial malperfusion.** When the value of rSO₂ decreases, the first and most important step is to rule out a mechanical obstruction to cerebral blood flow (CBF). For instance, in minimally invasive cardiac surgery, the endoclamping aortic cannula inserted through a femoral access could migrate in a position in the aortic arch where CBF could be acutely compromised. Also, with use of j-tip arterial cannula in ascending aorta malrotation of cannula can cause perfusion directly into innominate artery giving rise to unilateral cerebral hyperemia manifest as “harlequin facies” with an abrupt fall in contralateral rSO₂ and...
invariably associated with extensive cerebral injury unless detected.\textsuperscript{19} This occurs with a relatively greater frequency during congenital surgery and is one of the reasons why NIRS is increasingly employed during pediatric cardiac surgery.\textsuperscript{20} In such situations, if the carotid arteries are partially occluded or malperfused, the decreases in rSO\textsubscript{2} will be sudden and rapid, and once diagnosed, repositioning the aortic cannula can be easily effected with relief of malperfusion.

In adult patients, a relatively more frequent occurrence is cerebral malperfusion either as a consequence of ascending aortic dissection with occlusion of carotid lumen\textsuperscript{21} or kinking or obstruction of perfusion cannula during selective cerebral perfusion (SCP) for circulatory arrest procedures.\textsuperscript{22} There are increasing reports that bilateral rSO\textsubscript{2} monitoring is detecting contralateral desaturation during unilateral SCP (generally via innominate artery), with contralateral SCP via left common carotid cannula. This unilateral desaturation is most probably because of incomplete circle of Willis.

**Superior vena cava obstruction.** Because cerebral perfusion pressure (CPP) reflects the difference between inflow (mean arterial pressure [MAP]) and outflow (jugular venous) pressures, unrecognized cerebral venous obstruction via dislocation of the heart or venous cannula malposition can compromise cerebral perfusion. This has been well documented\textsuperscript{25,26} but may occur more frequently—even during non–pump beating heart procedures\textsuperscript{27}—than clinicians may appreciate. We have encountered such a situation in a cardiac transplant patient when cerebral venous return was compromised by a very tight superior vena cava cannula (Figure 4). It is also possible that the position of the head could impede venous return. Harvey et al\textsuperscript{2} recommend positioning the patient’s head when rSO\textsubscript{2} decreases to ensure that it had not been inadvertently rotated and also to observe for facial plethora.

**Step 2: Increase Mean Arterial Pressure**

The incidence of occult or overt cerebrovascular disease in the cardiac surgical population has been estimated at more than 50%,\textsuperscript{28} thus increasing the
potential for hypoperfusion because of impaired autoregulation and requirement for elevated CPP. One of the most common interventions in the treatment of brain desaturation is to maintain CPP as reported by Murkin et al.\textsuperscript{11} We try to maintain MAP within 15\% of baseline using vasopressors as required during CPB. However, if this intervention does not correct the abnormality, we would rapidly move to the next step.

### Step 3: Verify Systemic Oxygenation

Because it does not necessitate pulsatile flow, NIRS can also be used to confirm the presence or absence of peripheral desaturation in a variety of clinical settings. This can be particularly useful in patients with cardiovascular disease or in shock. The signals obtained from a noninvasive peripheral pulse oximeter are often absent in these critically ill patients because of the peripheral vasoconstriction. During CPB, pulse oximetry is nonfunctional, and cerebral oximetry has been used to detect sudden vaporizer failure, prior to any decrease in mixed venous oxygenation.\textsuperscript{29} Studies have also demonstrated the particular benefit of hyperoxia in preserving cells in ischemic cerebral penumbral tissue.\textsuperscript{30,31} Hyperoxia has not been shown to increase oxygen free radical generation,\textsuperscript{32} at least during rewarming after hypothermic circulatory arrest, and has been associated with less histological evidence of brain injury.\textsuperscript{33} Accordingly, we will increase fraction of inspired oxygen during CPB if previous measures have not restored rSO\textsubscript{2}. Unexpected brain and peripheral desaturation can also lead to specific diagnosis such as the detection of a nonsuspected cause of hypoxia such as an undiagnosed patient foramen ovale with associated right-to-left shunting (Figure 5).

### Step 4: Normalize PaCO\textsubscript{2}

One of the most powerful determinants of CBF is PaCO\textsubscript{2}, with the effects of hypocapnia and hypercapnia on brain circulation being well-known to clinicians. Yao et al.\textsuperscript{34} for instance, have observed that during hyperventilation the brain oximetry signals will be reduce, and during hypoventilation they will increase. Kolb et al\textsuperscript{15} described a protocol to determine acute cerebrovascular and ventilatory response to hypoxia. They measured flow velocity in the middle cerebral artery (MCAV) and rSO\textsubscript{2} observing that hypoxia was associated with a reduction in rSO\textsubscript{2}, whereas during hypercapnia both rSO\textsubscript{2} and MCAV increased. One of the most common causes of decreased rSO\textsubscript{2} is inadvertent hyperventilation after induction of anesthesia and during rewarming on CPB. Such unexpected brain desaturation can occur particularly during rewarming on CPB (Figure 6) when PaCO\textsubscript{2} may often be below 35 mm Hg. Normalization of PaCO\textsubscript{2} was the third most common intervention in a recent large prospective trial.\textsuperscript{11}

### Step 5: Optimize Hemoglobin

Hemoglobin is a key element in oxygen transport, and reduction in hemoglobin can be associated with reduction in rSO\textsubscript{2} values. Torella and McCollum\textsuperscript{36} have proposed that NIRS could be used as a monitor of blood loss. They monitored 10 blood donors during and for 10 minutes after blood collection.
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(470 mL) and observed a good correlation between blood losses and NIRS parameters. The significant reduction in hemoglobin because of acute hemodilution observed during initiation of CPB, combined with reduction in MAP because of decreased viscosity, is often reflected in decreased rSO2 with onset of CPB. Whether refractory low rSO2 values should be used as an indication for transfusion is currently contentious but may be beneficial when other interventions listed have proven ineffective.

Step 6: Evaluate Cardiac Function

During CPB, increasing pump flow is the most common and efficacious technique used in the correction of brain desaturations. In the noncardiopulmonary bypass conditions, few studies have reported the relationship between rSO2 and cardiac function. As cardiac performance is reduced, increased brain oxygen extraction would be encountered and lower brain oximetry values would be observed. In that regard, Madsen et al observed that rSO2 values are lower in patients with normotensive acute heart failure and improved with the treatment of heart failure. In addition, cerebral oxygen saturation has been shown to correlate with the presence of left ventricular dysfunction in patients with valvular disease during exercise testing. Lower cerebral saturation values were observed in patients who did not increase their cardiac output. To further explore the relationship between cardiac function and brain oximetry, C. Paquet et al (unpublished data, 2007) analyzed 99 patients using NIRS, pulmonary artery catheter, and transesophageal echocardiography. Significant correlations were observed between mean rSO2 values and central venous pressure (r = −.31), pulmonary capillary wedge pressure (r = −.25), mean pulmonary artery pressure (MPAP) (r = −.24), MAP/MPAP ratio (r = −.33), left ventricular fractional area change (<35, [35-50], ≥ 50), regional wall motion score index (r = −.27), and diastolic function. In practice, we will take steps to increase cardiac output or pump flow rate to correct rSO2 desaturations.

Step 7: Decrease CMRO2

If reduction in rSO2 values is observed despite the above measures, then a relative increase in CMRO2 or other processes may be operative. Cerebral hyperthermia may occur after rewarming during CPB and would be associated with reduction in rSO2 values through an increase in CMRO2. In this instance, measuring tympanic or nasopharyngeal temperature can detect this and should initiate brain cooling measures. For refractory cerebral desaturations during CPB, reduction of CMRO2 through deepening of anesthesia (eg, incremental bolus of propofol or thiopental) may be used.

Step 8: Other

In the presence of persistent low rSO2, particularly if unilateral, an intracranial process associated should be ruled out. Early postoperative neurological assessment with cerebral imaging might be considered. Finally, there is some evidence that laminar flow during CPB decreases CBF to a greater extent than pulsatile perfusion. In the setting of low rSO2 during CPB, pulsatile perfusion may be introduced, and we have noted improvements in rSO2 in certain patients.

Other Applications

Brain oximetry electrodes can also be used not only on the forehead but also in the periphery. F. Harel et al (J Clin Monitoring 2008, in press) from our institution have validated the use of NIRS as a monitor of peripheral perfusion and compared it to strain gauge and radionuclide plethysmography. An excellent correlation was observed between all these modalities. The combined use of both peripheral and central NIRS parameters has been reported in pediatric patients and
is useful to discriminate if a reduction in rSO₂ results from a central or peripheral process. Finally, the evolution of brain oximetry values during a procedure can be used to “tell the story” or evaluate and document several interventions (Figure 7).

**Limitations**

There are several limitations of brain oximetry that are important to recognize and have been the subject of several recent debates. As with any other monitoring modalities, false positives can occur. Therefore, before going through the algorithm, it is important to verify that the electrodes are well positioned and there is no light leakage as a consequence of peeling of the adhesive patch. Furthermore, only the anterior cerebral circulation is monitored clinically; therefore, hypoperfusion of the posterior cerebral territory could be missed. The NIRS device analysis algorithm assumes a fixed ratio of venous to arterial blood, which may vary in certain pathologic states, for example, cerebral edema. Finally, the success of any monitoring modality is contingent on the vigilance and intervention strategies employed by the clinician. In the context of cardiac surgery, it is essential that all the members of the cardiac team be aware of the utility of cerebral oximetry to maximize its benefit. Earlier studies had suggested clinical benefit but many had methodological limitations and none were randomized trials as of 2004. Since then, 2 randomized trials performed in single centers have demonstrated clinical benefit of cerebral oximetry when employed with a strategic intervention algorithm. Dissemination of a useful treatment algorithm is the primary purpose of the current article. Further multicenter studies are necessary to confirm the benefits and cost-effectiveness of this promising monitoring modality.

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