Topic Review

Near-Infrared Spectroscopy for Real-Time Cerebral/Somatic Oxygen Monitoring

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Near-Infrared Spectroscopy (NIRS) is a non-invasive, optical technique used to measure tissue oxygenation. Real-time, multi-site oximetry that enables simultaneous monitoring of regional oxygen saturation (rSO_2) of blood in both cerebral and somatic tissue beds is on pace to become a standard of care in pediatric cardiac surgery and critically ill pediatric patients. In vivo near-infrared spectroscopy enables continuous, non-invasive measurements of rSO_2 in brain and somatic tissue, providing a sensitive early warning sign of hemodynamic or metabolic compromise, enabling early and rapid intervention to prevent, or reduce the severity of, potentially life-threatening complications.

The key benefit of NIRS technology derives from the ability to measure blood oxygenation simultaneously and noninvasively in the brain—independently in the left and right hemispheres by placing sensors on each side of the forehead—and/or in somatic tissue. This provides real-time information on cerebral and peripheral blood oxygen saturation, allowing clinicians to detect and compare changes in rSO_2, identify critical events as they develop, monitor responses to acute interventions, and to document trends in oxygenation as they evolve over time.

NIRS takes advantage of the fact that the absorption spectrum of hemoglobin changes with the degree of oxygenation[a]. Using at least two wavelengths of near-infrared light, it allows the determination of the oxyhemoglobin fraction. At the heart of the NIRS system are light emitting diodes (LEDs) that send near-infrared light through skin and bone to the underlying tissues, and at least two photodetectors spaced 3-4 cm from the LEDs. When applied to the scalp, these two detectors allow the selective measurement of brain tissue oxygenation, a process known as spatial resolution. The photons are scattered, absorbed or reflected back to the sensors on the skin surface, a process known as reflectance oximetry. Based on the amount of light reflected back to the detectors—factoring in the energy absorbed by the skin and skull—the NIRS device determines the quantity of light absorbed by oxyhemoglobin and deoxyhemoglobin. The resulting ratio of oxyhemoglobin to total hemoglobin represents the regional blood oxygen saturation index of the tissue under the sensor[b].

Presently, the only FDA approved regional oximeter for simultaneous cerebral-somatic monitoring is the INVOS 5100C (pediatric and adult) (Somanetics Corporation, Troy, MI). This device is a continuous wave, spatially resolved spectrometer that measures changes in regional oxygen saturation (rSO_2). Since the algorithm assumes that 25% of the blood within the sample tissue is arterial and 75% is venous, the rSO_2 value is a venous weighted average that reflects the balance of oxygen supply and demand in the tissue under the probe. It parallels jugular bulb venous oxygen saturation ($SjvO_2$) when the probe is placed on the scalp. It parallels regional mixed venous oxygen saturation (SvO_2) when the probes are placed somatically. This technology had been validated in a number of published studies[c,d,e,f,g,h].

NIRS does not provide an absolute measure of oxygen saturation. Rather its value lies in monitoring trends in oxygenation levels. The device measures regional oxygen saturation continuously with changes displayed onscreen at 5-second intervals. Comparisons of real-time rSO_2 levels to the baseline values of individual patients—measured in the non-anesthetized patient at rest—reveal changes that reflect real-time fluctuations indicative of the patient's evolving hemodynamic status. When multi-site oximetry is employed, an approximation of SvO_2 can be obtained[i].

Monitoring of SvO_2 to gauge the adequacy of cardiac output and systemic oxygen delivery requires insertion of an indwelling catheter, with its accompanying risks including infection, bleeding and thrombus formation. The use of noninvasive cerebral/somatic oximetry to track blood oxygen can serve as a surrogate for SvO_2 and eliminate the risks and maintenance issues associated with indwelling catheters.

Multi-site monitoring may also reveal profound differences in tissue oxygenation surrounding different organ beds in part due to the ways the two circulatory systems operate[9]. The brain is a relatively high-extraction organ where blood flow undergoes minimal change in relation to sympathetic tone, while the kidney is a low-extraction, high-flow organ with high vein saturation and renovascular resistance that is highly influenced by sympathetic tone.

Clinical data in children and adults have demonstrated that a cerebral rSO_2 value less than 40%-50%, or a change in baseline greater than 20% are associated with hypoxic-ischemic neural injury[9]. Renal rSO_2 is typically 15% to 20% higher than brain rSO_2, and a declining renal rSO_2 is suggestive of developing circulatory impairment.[9] Any drops in rSO_2 toward or below these thresholds are cause to consider interventions.

Clinical Applications

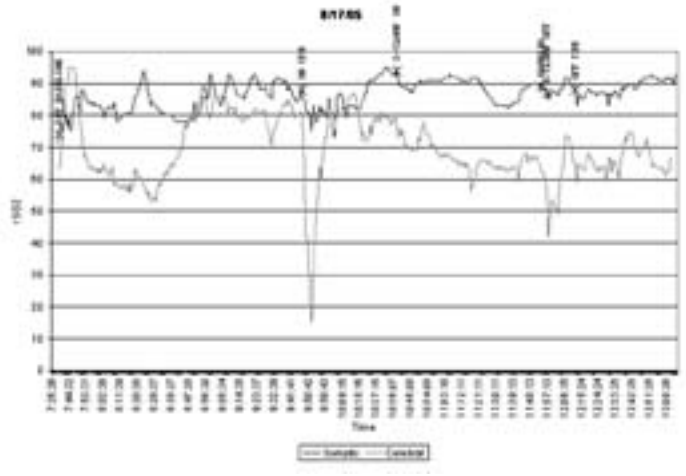
Rather than inferring brain or somatic oxygenation from indirect, systemic indices such as urine output, blood pressure and pulse oximetry, regional oximetry can provide a direct measure of blood oxygen saturation in brain and somatic tissue under the sensors. This often enables more rapid detection and intervention to prevent cerebral or somatic dysfunction and damage. The crucial extra seconds or minutes gained in initiating corrective interventions could prove life saving, as the margin of error is less in infants.

The benefits of utilizing NIRS in pediatric cardiac surgery are clear. Unlike finger pulse oximetry and some other traditional vital signs, rSO_2 readings do not depend on pulse, blood pressure or body temperature. Thus, rSO_2 values are particularly valuable when vital signs are weak or absent such as during cardiopulmonary bypass, hypothermic circulatory arrest, treatment of shock or cardiovascular collapse, and any deliberate or inadvertent interruption of regional blood flow (e.g., clamping, shifting cannulas, lifting the heart, etc). Studies have documented critical periods where the brain is at particular risk during cardiac surgery, such as during handling or dissection of the heart[j], on initiation of cardiopulmonary bypass[k], during deep hypothermic circulatory arrest[l], etc. Other studies and case reports have been published demonstrating that cerebral oximetry can detect bypass cannula or flow problems, prior to other parameters changing.[m,n]

Figure 1 represents a case from our institution. This was a 15.1 kg, four-year-old Hispanic male presenting for a residual ventriculo-septal defect (VSD) closure, infundibular muscle resection, right ventricular outflow tract (RVOT) reconstruction with a pulmonary homograft and bilateral pulmonary artery (PA) plasties. Upon initiation of cardiopulmonary bypass (CPB), the cerebral oximeter reading decreased from 80 to a low of 15 in four minutes. No other hemodynamic variables were abnormal during this period, including the somatic rSO_2. The blood pressure remained unchanged and the line pressure of the aortic cannula did not increase. The surgeon was notified and the aortic cannula was repositioned further out the aortic arch to a point distal to the takeoff of the left subclavian artery so that the tip was no longer hitting the back wall of the aorta. The cerebral rSO_2 reading immediately improved, returning to baseline within four minutes. The remainder of the case was uneventful. The patient recovered uneventfully without any neurological sequelae.

A report in *The American Journal of Surgery* on 143 infants and children concluded that a low pre-op rSO_2 value is predictive of perioperative mortality during repair of congenital heart defects on cardiopulmonary bypass[o]. Mean baseline rSO_2 was 65% for survivors compared to 47% for nonsurvivors (P = .0003). The association between pre-op rSO_2 <50 and subsequent perioperative mortality is

FIGURE 1



so strong that the authors suggest monitoring of rSO_2 may allow for improved pre-operative optimization of patients, with the potential for better outcomes. The authors also suggest it may provide additional information for family counseling.

In congenital heart patients needing to undergo a series of procedures, regional oximetry can also play a key role in the interventional cardiac catheterization lab. Here cerebral rSO_2 measurements can aid in the management of ventilatory status, airway patency and adequacy of brain perfusion. It can also provide an immediate indicator of disturbances to cerebral oxygenation upon inflation of balloon or occluder devices used during these procedures.

Regional oximetry is also invaluable for postoperative monitoring of critically ill pediatric patients. A study on neonates undergoing the Norwood procedure showed a significant (P = .029) association between prolonged low postoperative rSO_2 (>180 cumulative minutes of rSO_2 < 45%) and the presence of new or worsened ischemic brain lesions (as measured on pre-operative and post-operative MRIs)[p]. rSO_2 had a positive predictive value of 90% and a negative predictive value of 60%. This association did not apply to intra-operative factors, nor to traditional measures of overall cardiac output such as SvO_2 value, serum lactate level or acid-base status. Therefore, the authors concluded that the period during which ischemic brain lesions occur or progress may be postoperatively and that the usual clinical measurements in the CICU to assess global cardiac output might not reflect cerebral perfusion. Using cerebral and somatic oximetry in this time period may lessen the incidence of post-operative ischemia.

NIRS monitoring has also demonstrated value when used on somatic tissue beds. In high-risk neonates undergoing cardiac surgical procedures, postoperative renal dysfunction is a significant cause of morbidity. Though multi-factorial, dysfunction may be caused by renal hypoperfusion related to elevated renovascular resistance. Noninvasive monitoring of oxygen saturation in the kidney area can serve as an early indicator of changes in organ perfusion[q]. Somatic blood oxygenation assessed by rSO_2 on post-op day zero was predictive of the degree of renal dysfunction three days later. It was also found to be the strongest indicator of renal dysfunction, allowing for earlier interventions to improve perfusion and potentially minimize the risk of ischemic organ dysfunction or damage.

In summary, NIRS monitoring provides critical feedback on the patient's status in the operating room and in the ICU. It is becoming as invaluable as pulse oximetry.

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