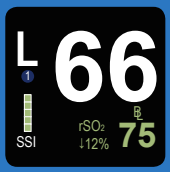
DETECTION AND CORRECTION OF **BRAIN OXYGEN IMBALANCE**

Surgical and Critical Care Applications of the INVOS™ Cerebral/Somatic Oximeter

Harvey L. Edmonds, Jr., Ph.D.



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DETECTION AND CORRECTION OF BRAIN OXYGEN IMBALANCE

Surgical and Critical Care Applications of the INVOS™ Cerebral/Somatic Oximeter

A POCKET GUIDE FOR CLINICIANS

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Learning Objectives

After reading this guide, clinicians should be able to:

- Describe the link between regional cerebral oxygen balance and the parameter used by the INVOS™ cerebral/somatic oximeter – regional oxygen saturation (rSO_2).
- Integrate brain rSO_2 information with other physiologic and clinical data before, during, and after surgery.
- Identify special situations that can influence cerebral rSO_2 monitoring.
- Discuss the clinical management and response to cerebral rSO_2 monitoring.

Dr. Edmonds received compensation from Covidien LP, a Medtronic company, for his professional time spent preparing this educational piece.

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Executive Overview

Regional oxygen saturation (rSO_2) monitoring systems permit the continuous noninvasive measurement of cerebral regional oxygen balance within the frontal cerebral cortex. Since cerebral rSO_2 represents an adjunct physiologic measure – local microcirculatory oxygen balance – it is important to appreciate the fundamental elements of this infrared light-based technology. This technology offers additional insights into patient clinical status; however, the novelty of the technology also makes it imperative for clinicians to review important situations and limitations that may influence rSO_2.

The noninvasive INVOS™ monitoring system is intended for use as an adjunct trend monitor of regional hemoglobin oxygen saturation of blood in the brain of an individual. It is also intended for use as an adjunct trend monitor of hemoglobin oxygen saturation of blood in a region of skeletal muscle tissue beneath the sensor in infants, children, or adults at risk for reduced-flow or no-flow ischemic states.

The prospective clinical value of data from the INVOS™ system has not been demonstrated in disease states. The INVOS™ system should not be used as the sole basis for diagnosis or therapy. Both randomized and nonrandomized controlled clinical trials have shown the positive impact of INVOS™ system-guided patient management on patient outcomes. Randomized clinical trials have shown that INVOS™ system monitoring using a standardized interventional protocol provides improved clinical outcome and resource utilization.[1-4]

For complete information about the INVOS™ system, refer to the service manual/instructions for use.

rSO_2: A Clinically Validated Measure of Regional Brain Oxygen Balance

Brain Oxygen Balance Monitoring with Near-infrared Spectroscopy (NIRS)

Intracranial rSO_2 measurement by NIRS is possible because the human skull is translucent to infrared light. As with other forms of clinical oximetry, saturation determination relies on multiple wavelengths of light to discriminate between the unique absorption spectra of oxyhemoglobin and deoxyhemoglobin (Figure 1). Generally speaking, within the wavelength region of interest (i.e., spectrum), the only other competing infrared absorbers (i.e., chromophores) are water and the skin pigment melanin (Figure 1). Consequently, the non-heme chromophores have the potential to influence NIRS-based oxygen saturation measurement.[5,6]

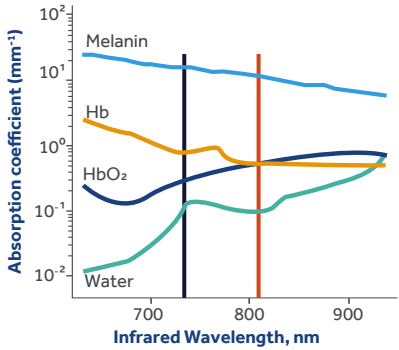


Figure 1. Photon absorption in the cranium. The cranium contains four substances that absorb photons with wavelengths in the near-infrared range (i.e., 680-900 nm).

The INVOS™ System

The INVOS™ system employs disposable sensors with an integrated near-infrared light source and photodetector that can be applied to each side of the forehead for monitoring blood in the brain. This placement permits monitoring of the ischemia-susceptible cortical tissue in the border zone between the anterior and middle cerebral arteries but may preclude detection of posterior border-zone oxygen imbalance or perfusion abnormality.[7,8]

Figure 2a arises from a landmark NIRS imaging study that offered the first visual confirmation that the mean path of tissue-reflected photons in the adult human brain is parabolic. In addition, one can see that the photon penetration depth below the skin is approximately half the photon source-detector separation distance.[9] The cerebral tissue sample volume has been estimated to be ~1.5 cc.[10] Since there is sufficient photon-absorbing hemoglobin in larger vessels to trap all incident infrared light, surface-detected infrared reflections arise exclusively from blood vessels <1 mm in diameter (i.e., tiny arterioles, capillaries and small venules). All current FDA-cleared tissue oximeters assume a constant arterial:venous ratio within this microcirculation. The INVOS™ systems utilizes a fixed 25:75 ratio. However, the actual ratio may vary substantially among subjects and within an individual over time.[11]

In the young healthy adult brains assessed in this imaging study, a source-detector distance of 30 mm permitted cortical measurement, since the average skin-cortex distance (SCD) was ~10 mm. However, Figure 2b documents that SCD may increase by 50% in elderly patients. In this case, photons arising from optodes utilizing a source-detector distance <30 mm may not penetrate underlying cerebral cortical tissue.

The INVOS™ system uses an optode containing a pair of photo detectors and a proprietary analytical process termed Spatial Resolution Spectroscopy (SRS) (Figure 2c). This technology suppresses the influences of extracerebrally reflected photons and inter-patient variations in photon-intracranial tissue coupling, since they are common to both sample measurements.[11] SRS is based on the intensity relationship of light reflected from neighboring "shallow" (30 mm source-detector separation) and "deep" (40 mm) regions of the cerebral cortex. The SRS approach enabled the first verification of the cerebral cortex as the anatomic source for an adult forehead NIRS signal in carotid endarterectomy patients.[11]

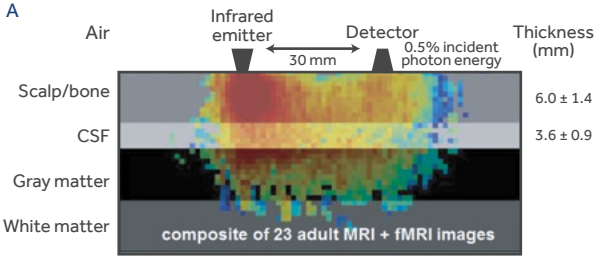
Observations during retrograde cerebral perfusion demonstrated that the INVOS™ system's rSO_2 determination is relatively insensitive to substantial shifts in this ratio.[12] In addition, rSO_2 differs from other oximetric technologies such as pulse oximetry (SpO_2) and jugular venous oxygen saturation ($SjvO_2$), because it does not require actively flowing blood, either pulsatile or non-pulsatile. In neonates (Figure 2d), this optode geometry may produce an intracranial photon path that includes subcortical white matter.[13]

The shallow, deep signal ratio results in a rSO_2 measure that is ~70% intracranial and independent of interpatient variation in photon scatter.[14]

Currently, rSO_2 provides the only noninvasive method to continuously monitor changes in local brain oxygen balance.[11,14]

Figure 2.

A



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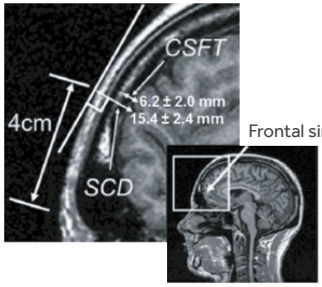

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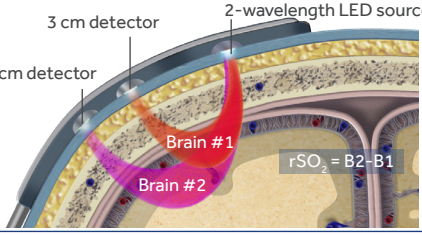
C

Spacially Resolved Spectroscopy (SRS)



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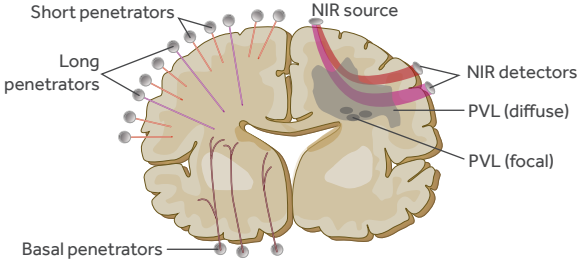

Figure 2. Depth of the INVOS™ monitoring technology in adults and neonates. Figure 2A shows the first published image of the actual transcranial photon pathway in the adult human brain during NIRS measurement.[9] Superimposition of the composite functional near-infrared spectroscopy (fNIRS) image from 23 young healthy adult subjects onto the related MRI image provided anatomic detail. Note the parabolic banana-shaped transcranial pathway and the minimum scalp-to-cortex distance (SCD) of 11 mm. Energy in the tiny bioelectric signal reaching the optode detector is only 0.5% that of emitted energy. The preoperative cranial MRI image shown in Figure 2B summarizes the results obtained from 223 elderly (67±12 yr) cardiac surgery patients.[15] SCD was measured from optimal NIRS optode location 4 cm superior to the superciliary arch to the closest cerebral cortical surface. The 15 mm average SCD was 50% larger than that observed in young healthy adults.[9] This, and other recent studies support the principle that an NIRS emitter-detector distance >25 mm is necessary for reliable rSO_2 measurement in most adult patients.[16] Figure 2c illustrates the concept of the proprietary Spatially Resolved Spectroscopy technology. A pair of photo detectors are strategically located to ensure that each measures photons reflected from different neighboring regions of the cerebral cortex. Individual differences in the optical properties of extracerebral and intracortical tissues are suppressed, since they are common to both cortical samples. Direct measurement of cortical and extracortical oxygen saturation has shown the approximately two-thirds of the INVOS™ systems transcranial rSO_2 measurement arises from brain tissue.[14] As shown in Figure 2D, the very small SCD and thin cortical layer of neonates implies that a substantial portion of the rSO_2 signal represents subcortical white matter.[13]

Validation of rSO_2 as a Measure of Brain Oxygen Balance

Compared with other oximetric technologies such as SaO_2 and $SjvO_2$, verification of brain rSO_2 accuracy remains technically challenging. In the absence of a true reference, manufacturers and the U.S. Food & Drug Administration have adopted a proxy called field saturation (fSO_2).

This metric, $k_1(SaO_2) + k_2(SjvO_2)$, was developed by an early INVOS™ system clinical investigator to assess cerebral oximeter performance.[17] The manufacturer-specific constants k_1 and k_2 are empirical estimates of the arterial and venous blood contribution to proprietary rSO_2 algorithms.

A peer-reviewed report describes statistically significant correlations between fSO_2 and the INVOS™ monitor rSO_2 in healthy adults breathing room air as well as hypoxic and hypercapnic mixtures (Figure 3).[18] Without a true reference standard, however, regional cerebral oxygen saturation accuracy is indeterminate and the interpretation of device comparisons is complex and uncertain.

Clinicians should appreciate that momentary rSO_2 values and trending characteristics are machine specific and are not interchangeable among different oximeter brands.[19,20] As a result, it is unjustified to use clinical data generated from one proprietary rSO_2 system to "validate" the utility of a competing device.[19,21]

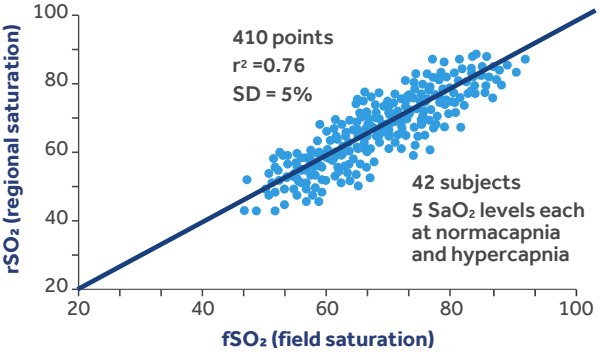

Figure 3. Correlation between rSO_2 and fSO_2. Cerebral oximeter performance is assessed by comparing rSO_2 values to a proxy for brain saturation termed field saturation (fSO_2). This graph, derived from the study of Kim et al. (2000),[18] shows statistically significant correlation between rSO_2 and fSO_2 in a group of adult volunteers exposed to graded levels of hypoxia and hypercapnia.

Normative Brain rSO_2 Values

Normative brain rSO_2 values are an absolute requirement for the definition of abnormality. For the INVOS™ systems, Heringlake et al. found in large sample of conscious adult cardiac surgery patients that the median normative rSO_2 was 66% (Figure 4).[22] It is particularly noteworthy that in the high-risk cohort, pre-operative rSO_2 was a better predictor of post-operative morbidity and mortality than the EuroScore. Values <50 were thus statistically subnormal. A left versus right hemisphere asymmetry of >10% occurred in only 5% of patients.

Recently, multiple studies have confirmed both the cardiac patient normative values and asymmetry incidence (Figure 4).[23,24] It is noteworthy that $SjvO_2$ asymmetry >10% occurs in a majority of patients.[25] Thus, physiologically appropriate comparisons of rSO_2 and $SjvO_2$ require that both measurements invariably be made from the same side of the head.

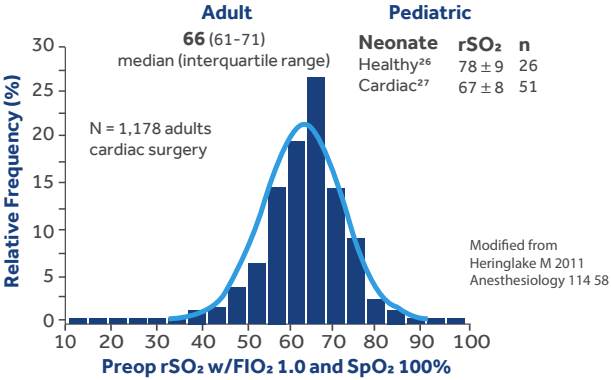

Figure 4. Sample rSO_2 data. The graph shows the frequency distribution of rSO_2 values obtained preoperatively from 1,178 adult cardiac surgery patients.[22] Since the values are normally distributed, both the median and similar mean describe the distribution central tendency. Statistical abnormality representing the lowest 5% of the values occurs at an rSO_2 of 50. Similar results were obtained in a recent larger study involving 2097 adults.[24] Normative data for younger patients are currently based on much smaller patient samples.[26,27]

Brain rSO_2 Monitoring Before, During, and After General Anesthesia

Preprocedure (baseline) rSO_2

INVOS™ monitoring technology does not require establishment of a preprocedure baseline reference. As with intraoperative blood pressure monitoring, however, obtaining baseline information is sound clinical practice.[28] Baseline rSO_2 values can help stratify presurgical patients with respect to risk of mortality, morbidity, and postoperative delirium.[22,24] Moreover, preprocedure bilateral rSO_2 values can alert the clinician to technical difficulties in need of immediate correction or valid pre-existing symmetric or asymmetric subnormal values.

Collection of reliable baseline rSO_2 values is influenced by proper recording technique. Prior to optode (i.e., disposable sensor) application, patient forehead skin oil should be removed with an INVOS™ system-provided acetone wipe. If the forehead is exposed to intense light (i.e., direct forehead illumination by surgical lights) or heat sources (i.e., fluid or body warmers), the optodes should be covered with an opaque material. In adults, the optode light source and detectors should be placed "3 cm above the superciliary line" with the long axis parallel to the intra-aural line. Consistent positioning in this manner minimizes inter- and intrasubject baseline rSO_2 variation and avoids the potentially confounding effects of the frontal sinus on light scattering.[15,29] Repeated optode use is not recommended because the accumulation of epidermal debris on the adhesive surface may have unpredictable effects on extracranial photon scattering.

Prior to monitoring, INVOS™ system recording quality should be assessed by inspection of the signal strength index for each channel (Figure 5). The five-unit bar scale is nonlinear. Thus, the one-bar signal strength is only 4% of that represented by five bars. Adequate signal strength is represented by the continuous display of more than one bar.

Figure 5. INVOS™ monitor. The green vertical five-bar signal strength indicators are shown for each INVOS™ recording channel. Signals with a stable reading of more than one bar are sufficiently strong to permit reliable monitoring. Large font numbers display the momentary rSO_2 values for each channel, which are updated every 5 seconds. Mid-size font numbers display the baseline values. Red numbers reflect an oxygen debt alarm, and the small font values display the percentage change from baseline.

Positioning

A sudden symmetric or asymmetric rSO_2 decrease may occur during anesthetic induction, pulmonary artery or central venous catheter insertion, or final positioning (Figure 6).

Without accompanying change in blood pressure or respiratory gases, precipitous rSO_2 decline can help identify an otherwise unrecognized cerebral blood inflow or outflow obstruction.[30,31]

With cardiac and vascular surgery, the unexpected development of regional brain oxygen debt may be the consequence of a failure of the oxygen delivery system, or a malpositioned heart, arterial cannula, perfusion cannula, vascular clamp, ligature, or cardiac vent.[32-34]

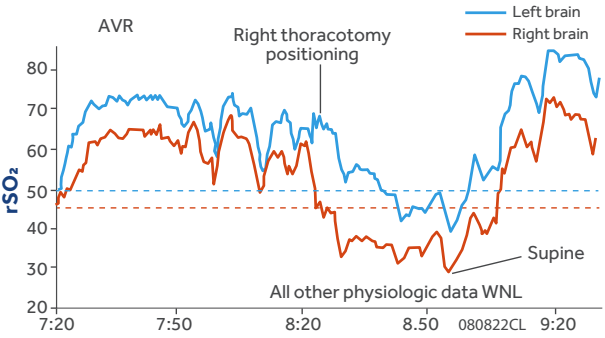

Figure 6. INVOS™ system and patient positioning. INVOS™ monitoring technology detected rSO_2 decline. Oxygen balance returned to normal with restoration of the supine position, and the surgery proceeded without incident.

CO_2 Influence on rSO_2

Cerebral arteries in the healthy brain are exquisitely sensitive to hydrogen ion shifts and consequently CO_2 change. CO_2 accumulation results in arteriolar vasodilation and attendant rSO_2 increase.[35,36] Of note, the CO_2-mediated rSO_2 rise accompanying endotracheal intubation provides a simple method to verify bihemispheric normal vascular responsiveness (Figure 7).

Since cerebral CO_2 reactivity is a precondition for autoregulation, its absence signifies increased risk of potentially injurious oxygen imbalance and hypoperfusion (Figure 8).[37] With this knowledge, rSO_2-guided blood pressure management may then be used to help avoid hypoperfusion injury. The individualized CO_2:rSO_2 relationships are also important during cardiopulmonary bypass to optimize acid-base management.[38] With CO_2-unreactive cerebral arterioles, the risk of brain hypoperfusion is increased, and the perfusionist has a diminished opportunity to improve brain oxygen balance via adjustments in acid-base management.

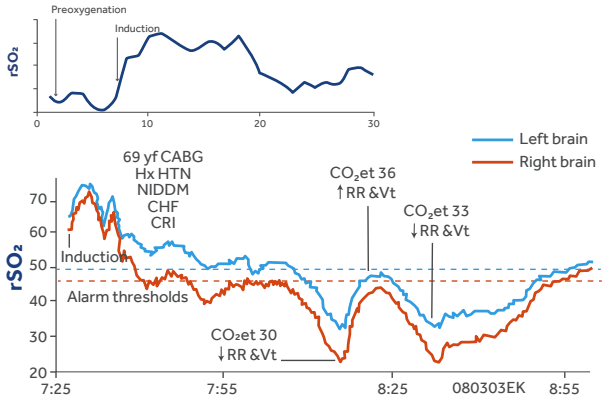

Figure 7. INVOS™ system and CO_2 accumulation. The inset graph at upper left shows the normal response to pre-oxygenation and anesthetic induction. The large graph also shows large rSO_2 increase with endotracheal intubation, suggesting normal cerebral arteriole CO_2 reactivity. Multiple hypocapnic episodes consistently resulted in brain oxygen debt. Each was promptly corrected by appropriate adjustments of the respiratory rate (RR) and tidal volume (Vt).

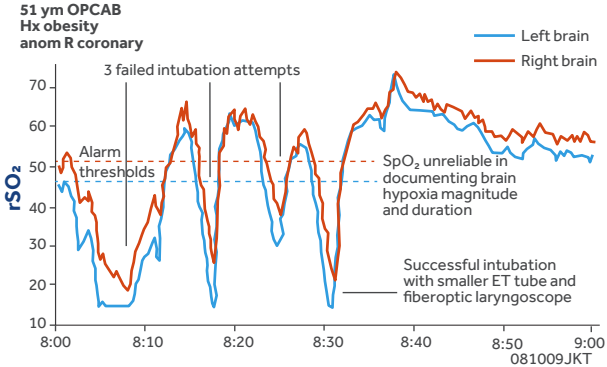

Figure 8. INVOS™ system and hypoperfusion. rSO_2 trends were notable initially for abnormally low and asymmetric baseline values. The trends then precisely quantified the extent of brain oxygen debt associated with three failed intubation attempts and documented the ultimately successful fourth attempt.

Systemic and Regional Hypoxemia Influences on rSO_2

The physiologic properties of brain rSO_2 make it uniquely suited for the early detection of developing hypoxemia. Inspection of the familiar oxygen dissociation curve emphasizes that SvO_2 or venous-weighted rSO_2 will change more than SaO_2 or SpO_2 to a fixed decline in blood oxygen partial pressure (Figure 9). This fact combined with the extraordinarily high brain oxygen demand results in the observation that developing hypoxemia often appears first in brain rSO_2 (Figure 8).[39,40] Even with the extensive physiologic monitoring used during cardiac surgery, evidence of inadequate oxygen delivery may be first observed because of a declining cerebral rSO_2.[41]

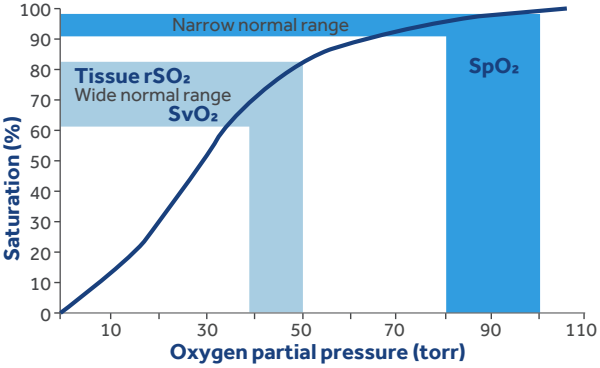

Figure 9. INVOS™ system and hypoxemia. The oxygen dissociation curve illustrates the differential sensitivity of arterial and venous dominant O_2 saturation measures to small changes in oxygen partial pressure. This differential sensitivity helps explain the observation that cerebral rSO_2 routinely detects developing oxygen imbalance before pulse oximetry.

Blood Product and Fluid Management Influences on rSO_2

In the low-to-normal range (i.e., hematocrit <30%), hemoglobin and rSO_2 are linearly related, while at a higher hematocrit, their relationship vanishes or may become inverse.[42] This hemoglobin dependency explains the often observed transient rSO_2 decline at the onset of cardiopulmonary bypass. Initial passage of a crystalloid prime solution through the cerebral circulation momentarily lowers brain hemoglobin. It also should be appreciated that blood product administration will not invariably result in an increase in rSO_2. Naidech et al. (2008) noted a wide variation in brain rSO_2 responses to administration of packed red cells (Figure 10).[8]

Occasional declines in rSO_2 should be expected, since stored red cells may have their oxygen-carrying capacity diminished by up to 90%.[43]

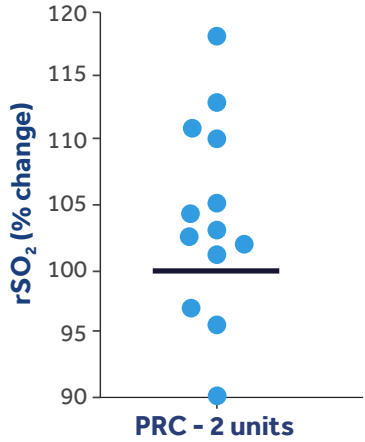

Figure 10. rSO_2 and blood product administration. The results of this small study illustrate the marked variation in rSO_2 response to administration of two units of packed red cells (PRC). (The graph is based on data from Naidech et al. 2008.)

Anesthetic Influences on rSO_2

Nearly two-thirds of cerebral oxygen is utilized to support interneuronal signal transmission.[44] Thus, anesthetic influences on rSO_2 depend on the neuropharmacologic properties of each agent and its dose. Volatile halogenated anesthetics, barbiturate hypnotics, and propofol have profound cortical suppressant activity, while opioid analgesics and benzodiazepine amnestic agents generally do not. Rising doses of the powerful cortical suppressant anesthetics may increase rSO_2 as oxygen consumption is decreased.[45] Conversely, a sudden rSO_2 decrease may signify decline in anesthetic effect (Figure 11).

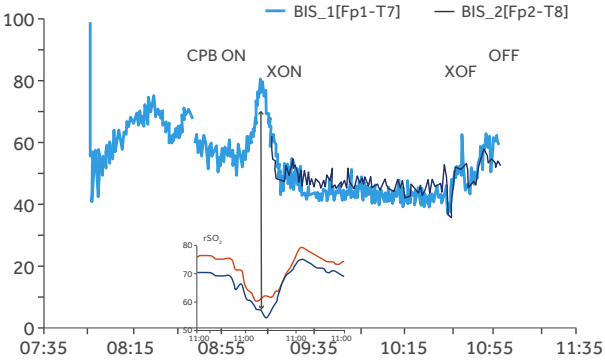

Figure 11. INVOS™ system and anesthesia. At the onset of total cardiopulmonary bypass, brain responses to an initially unrecognized empty anesthetic vaporizer are shown. The increased cerebrocortical neuronal activity bilaterally increased EEG bispectral index and decreased brain oxygen balance (i.e., rSO_2). All values normalized with vaporizer refilling.

Brain Temperature Management Influences on rSO_2

The neuroprotection afforded by hypothermia is due in part to reduced brain oxygen demand. However, individual patient responses to cooling vary widely. Thus, decreasing cranial temperature does not automatically ensure an adequately neuroprotective cerebral hyperoxic state.[46] Wide variation in cooling response is due to patient-specific cerebral hemodynamics as well as mechanical perfusion strategy/ tactics.[47] For example, the enhanced cerebral blood flow and cooling efficacy afforded by temperature-corrected (i.e., pH-stat) acid-base management improve neurologic outcome in both pediatric and adult patient cohorts undergoing cardiovascular surgery with deep-hypothermic circulatory arrest.[48] Yet the magnitude of hypothermic neuroprotection in individual patients depends in part on the bihemispheric responsiveness of cerebral arterioles to change in hydrogen ions and CO_2.

Cerebral oximetry gives anesthesia providers and perfusionists this key information at the start of surgery to guide patient care plans and optimize hypothermia management (Figure 12).

Regional brain hypoperfusion associated with suboptimal cooling may lead to transient cerebral vasoparesis (i.e., vasoneural uncoupling).[49,50] As a result, during rewarming an inverse relationship between brain temperature and rSO_2 has been described in both adult and pediatric cardiac surgery patients. Prompt detection and treatment of this flow-metabolism mismatch may help avoid ischemic brain injury.[51,52]

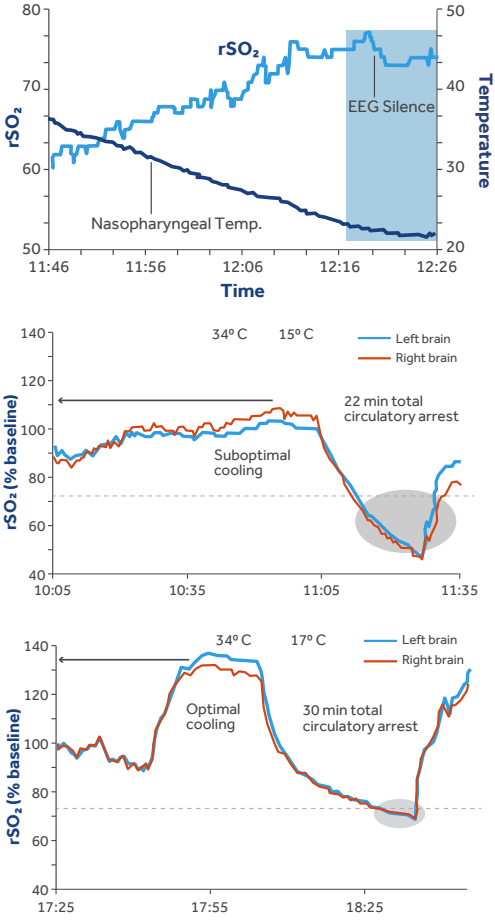

Figure 12. INVOS™ system and brain temperature. The left graph shows the expected inverse relationship between cranial temperature and brain rSO_2. Note that the rSO_2 rise reaches an asymptote at ~23°C and that further cooling does not create more regional hyperoxia. At lower right, the graph illustrates an optimal cooling response conducted with pH-stat acid-base management in a patient with CO_2-reactive cerebral arterioles. Marked hyperoxia prevented oxygen debt development during later total circulatory arrest. In contrast, the upper right graph depicts suboptimal cooling with alpha-stat acid-base management. Minimal hyperoxia resulted in a large oxygen debt during total circulatory arrest.

Supplemental Cerebral Perfusion Influences on rSO_2

During deep-hypothermic circulatory arrest, rSO_2 declines of >30% below baseline are highly associated with new neurologic deficit.[53] Numerous studies have demonstrated that the "safe time" for systemic circulatory arrest may be extended with the use of bilateral rSO_2 monitoring to ensure adequate retrograde or selective antegrade cerebral perfusion (Figure 13).[54,55]

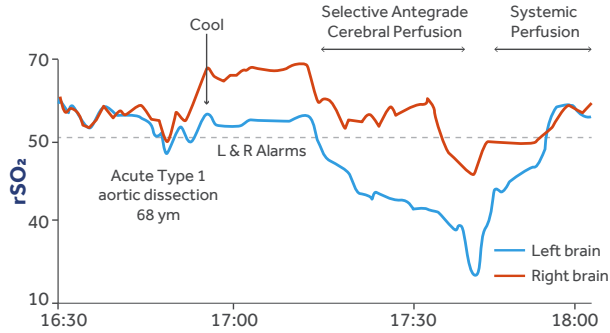

Figure 13. Supplemental cerebral perfusion. Because of the hemodynamic characteristics of this acute type I aortic dissection, upper body cerebral perfusion was mechanically supported through a right axillary perfusion cannula. However, cerebral perfusion was not symmetrically supported. Cooling and selective antegrade cerebral perfusion were more efficacious on the right side. rSO_2 verified adequate right hemisphere perfusion throughout the emergent procedure.

Table 1 provides a summary of pre-incision considerations for INVOS™ monitoring technology.

Table 1. Pre-incision bilateral rSO_2 assessment

Define	Consider
Signal strength index (SSI)	▪ Signal reliable with stable SSI >1 bar. ▪ If signal unreliable, check cable and reposition/replace optode.
Preprocedure baseline	▪ rSO_2: <50 or >80 is outside normative range. Right vs. left rSO_2 >10% indicates asymmetry. Rule out technical cause for abnormality. ▪ Check patient history, cardiopulmonary and hemodynamic status, hemoglobin/hematocrit.
O_2D Alarm Threshold	▪ If rSO_2 is normal, set alarm at 20% <baseline. ▪ If rSO_2 is subnormal, set alarm at baseline.
Pre-oxygenation response	Low O_2 reserve with rSO_2 increase >5%.
Endotracheal intubation response	Low CO_2 reactivity with rSO_2 increase <5%.

Special Issues Impacting Brain rSO_2 Monitoring

Hundreds of peer-reviewed studies demonstrate that, despite the potential for artifact and other issues, reliable INVOS™ monitoring technology of rSO_2 values can be obtained in many patient care settings.[56-58] However, in certain circumstances, momentary rSO_2 values may not accurately reflect regional brain oxygen balance. Some of the following examples emphasize the importance of rSO_2 trends in signal interpretation. As noted, INVOS™ monitoring technology is an adjunct to clinical judgment, not a substitute for it.

Extreme examples of this inherent physiologic limitation are the reports of normative rSO_2 values that were obtained from human cadavers or chromophore-containing inanimate objects like pumpkins.[59,60] Cadaveric rSO_2 values may be normal because postmortem cerebral venous oxygen saturation ranges widely from 5% to 95%, depending on the cause of death and body storage conditions.[61,62] Similarly, a normative rSO_2 reading may be obtained from pumpkins because the value depends simply on the spectrophotometric measurement of nonpulsatile reflected light.

Conversely, artifactually low rSO_2 values may be attributable to[63-69]:

1. Optode positioning over an intracranial photon sink (i.e., intracranial venous sinus or hematoma)
2. Excessive photon scattering (i.e., hair or hair follicles)
3. Cranial bone anomaly or frontal sinus inflammation
4. Presence of infrared-absorbing intracranial or intravascular pigments or dyes
5. Dyshemoglobinemias

Cerebral Hyperperfusion

The vast majority of clinical rSO_2 studies have focused on brain injury from hypoperfusion and oxygen debt. However, cerebral hyperperfusion manifested by hyperoxia is also potentially injurious. Underperfused brain shifts to anaerobic metabolism for survival. Resulting lactic acidosis dilates cerebral arterioles in affected regions. Consequently, a benign transient hyperemia typically appears with restoration of normal perfusion. For example, after termination of vascular occlusion during carotid endarterectomy or carotid angioplasty and stenting, ipsilateral cerebral hyperoxia (i.e., rSO_2 increase >10%) generally appears within 3 minutes and normalizes within 20 minutes (Figure 14).[70] Alternatively, a pathologically persistent (i.e., >24 hours) hyperemia may produce vasogenic edema and a cerebral hyperfusion syndrome characterized by migraine symptoms, delirium, focal neurodeficit, and seizures.[71] The syndrome may develop with "normal" blood pressure and may be undetectable by tomographic brain imaging.[72] Ogasawara et al. (2003) found the incidence of SPECT- confirmed pathologic postendarterectomy hyperperfusion to be 12%.[73] These authors showed cerebral oximetry to have 100% sensitivity and specificity in detecting this hyperperfusion. Other investigators have reported on the value of rSO_2 in detecting hyperperfusion accompanying retrograde or selective antegrade cerebral perfusion during aortic arch surgery.[74]

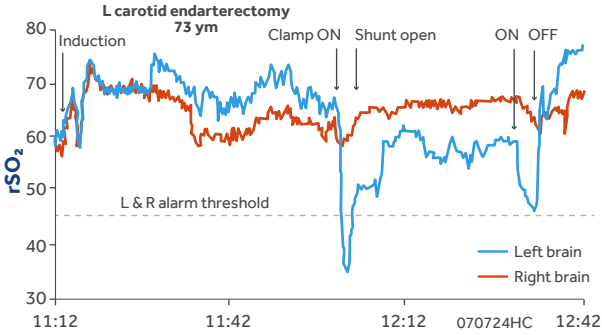

Figure 14. Cerebral hyperperfusion. During carotid endarterectomy, rSO_2 detects normal brief reactive cerebral hyperemia (>10% rSO_2 above baseline) immediately after artery declamping. Persistent elevation >1 hour warns of a potential pathologic cerebral hyperperfusion syndrome.

Seizure Activity

Cerebral vasoneural coupling ensures that local brain metabolic increases normally are met with augmented regional blood flow.[75] These rapidly oscillating rSO_2 trends have been used successfully to detect seizure activity in chemically paralyzed, ventilated patients and monitor patient response to anticonvulsant therapy.[76] Clinically silent seizures occur frequently in neurocritical care patients and, if left untreated, may adversely affect outcome.[77]

Cerebral Vasospasm

The presence of intracranial extravascular blood may trigger arterial vasospasm. Resulting local hypoperfusion may disrupt normal vasoneural coupling. As with seizure activity, the destabilized hemodynamic response can then lead to oscillation in rapidly updated rSO_2 trends.[78] INVOS™ monitoring technology recordings from shaved scalp overlying a spastic arterial segment successfully recorded vasospasm progression and a subsequent positive therapeutic response.[79]

Intracranial Hypertension

Cerebral rSO_2 is inversely related to intracranial pressure in critical care patients with brain tumors, head trauma, or hydrocephalus.[80] In all three pathologic conditions, intracranial hypertension is associated with a significant rSO_2 reduction, signifying developing brain O_2D. NIRS monitoring showed promise in a pilot study as part of an autoregulation-guided treatment for TBI.[35] However, the presence of intracranial extravascular blood may confound this relationship because of infrared photon sequestration. It should also be appreciated that rSO_2 values obtained from dying or dead brain are typically very high because there is little or no oxygen consumption.[81] This observation helps explain the lack of a linear relationship between cerebral blood flow and rSO_2. Furthermore, large shifts in intracranial photon scattering that accompany brain swelling may profoundly alter rSO_2 in an unpredictable manner.

Clinical Management: Responding to Brain rSO_2 Changes

rSO_2 fluctuations may be observed with the INVOS™ monitor. However, variability in rSO_2 values when seen during a single hemodynamic fluctuation – for example, a change in blood pressure – are not necessarily clinically significant; specific consideration should be given to a large decrease (i.e., >20%) or increase (i.e., >10%) in rSO_2 from a preprocedure or other reference point. A systematic approach is presented to guide detection and correction of noteworthy brain oxygen imbalance. It remains an evolutionary process that has emerged from earlier published algorithms.[2,4,82-85]

There are currently three multi-center clinical trials demonstrating that the consistent use of an INVOS™ technology-derived intervention algorithm successfully corrects episodes of noteworthy cerebral oxygen desaturation. An 8-center U.S. trial in 235 adult cardiac surgery patients achieved an 80% correction rate, while an 8-center Canadian trial corrected 97% of the episodes.[82,83] A European multi-center trial involving 67 extreme preterm neonates obtained an 85% success rate.[84] Consistent success of the algorithm in institutions with widely divergent practice patterns and patient populations suggests that the algorithmic approach has general applicability.

Table 2 presents a newly updated, objective, systematic, stepwise rSO_2 assessment process.

Table 2. Assessment of cerebral oxygen imbalance (observations and considerations with the INVOS™ system).

Observe	Consider
rSO_2 directly correlated with change in BP	Dysautoregulation
rSO_2 and ↑ BP inversely correlated	Vasoconstrictor hypoperfusion
rSO_2 and ↓ BP uncorrelated	▪ Airway inadequacy ▪ Ventilation abnormality (i.e., hypocapnia) ▪ Anesthetic delivery inadequacy ▪ Cardiopulmonary/ CPB dysfunction ▪ Blood loss/hemodilution ▪ Nonpulsatile perfusion ▪ Brain temperature increase ▪ Intracranial hypertension
rSO_2 ↑ BP uncorrelated	▪ Cerebral hyperemia ▪ Brain temperature decrease ▪ Pulsatile perfusion reestablished ▪ Low O_2 reserve with rSO_2 increase >5%
rSO_2 asymmetry appearance	▪ Patient malposition ▪ Heart malposition ▪ Cannula, catheter, clamp, or vent malposition ▪ Low CO_2 reactivity with rSO_2 increase <5%
rSO_2 trend rapid oscillation	▪ Seizure-like activity ▪ Cerebral vasospasm

Summary

This pocket guide has discussed how rSO_2 monitoring may be used most effectively in the surgical and critical care environments to detect and correct regional brain oxygen imbalance. It is important for clinicians to fully appreciate the applications, limitations, and special considerations for use of INVOS™ monitoring technology.

Evidence in the literature documents patient and economic benefits resulting from the use of INVOS™ monitoring technology. These clinical investigations provide an evidence-based rationale for the incorporation of INVOS™ monitoring technology as a tool to facilitate intraoperative and critical care management.

Depending on the specific patient characteristics and clinical situation, the use of INVOS™ monitoring technology may be a very appropriate decision. However, the decision to use the INVOS™ system should be made on a case-by-case basis by the individual practitioner.

As clinical experience and investigation continue, clinicians are encouraged to stay current with available literature regarding the use, benefits, and limitations of INVOS™ monitoring technology to guide patient care. Additional clinical information and other educational resources can be accessed at www.covidien.com/PACE.

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Notes

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