Near-Infrared Monitoring of Brain and Tissue Oxygenation: Is the Monitor on the Right Person?

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Disclosures and Conflicts

- Conflicts: clinical research support from NIRS manufacturers (CAS Medical, Nonin)
- Off-label use: most of the NIRS technologies discussed are FDA-approved for infants and children; all drugs mentioned will probably be off-label and/or without specific indications in infants and children
Goals

• Outline clinical need
• Overview of NIRS technology
• Show some representative data
• Summarize available clinical data supporting and limiting enthusiasm for clinical use
• Discuss next steps
**Clinical Need**

- Improved surgical outcomes, survival
- Shift in focus to longer-term, quality of life issues
- “Brain injury”, especially neurocognitive dysfunction, remains a significant and essentially unchanged problem despite numerous investigations and interventions over 20-30 years
NIRS Basics

- First described by Jobsis in 1977\(^1\)
- Regional oximetry (also called tissue or cerebral oximetry) uses light to assess oxygen levels in all tissues beneath the sensor.
- Regional oximetry is a mixed-venous assessment of tissue oxygenation that uses spatial resolution to assess oxygen status.
- Cerebral tissue oxygen saturation (rSO2) is 60-80% in normal, healthy patients.

NIRS Basics: Beer Lambert Law

- Beer-Lambert Law: absorption of light is related to the properties of the material/distance it is traveling through.
  - Specific wavelengths to isolate specific chromophores (hemoglobins, myelin, melanin, other heme proteins)

\[
\log\left(\frac{I_1}{I_0}\right) = -\varepsilon C l
\]
NIRS Basics

- As hemoglobin binds/releases oxygen it absorbs and reflects different wavelengths of light.
- By using multiple wavelengths of light in the near-infrared spectrum, to which tissue is relatively transparent, we can measure that change.
NIRS Cerebral and Tissue Oximetry Values are Calculated and Based Upon Several Critical Assumptions

- **This Hb Component**
  - Arterial Saturation: $\text{SaO}_2$
  - Venous Saturation: $\text{SjvO}_2$

- **Should be**
  - Arterial Saturation: 95-100%
  - Venous Saturation: >50%

- **As a Percent of Blood**
  - $30\% = 0.30$
  - $70\% = 0.35$

- **Added Together**
  \[ \text{rSO}_2 = 0.30 + 0.35 = 0.65\% \]
Tissue Oxygenation

Local SaO2

Capillary

Local SvO2

Arteriole

Tissue “sees” approximately 1/3 oxygenated and 2/3 venous blood

Venule
NIRS Regional Tissue Oximetry?

- A non-invasive, continuous measure of oxygenation status in specific tissue bed.
- Tissue oximetry assesses the relative balance of oxygen supply and demand at the site.
• Cerebral NIRS tracts most closely with “mixed venous” O2 saturation and hence cardiac output/O2 delivery
• Decreased somatic NIRS (including renal and splanchnic) may also reflect early decreased systemic perfusion due to sympathetic activation and peripheral vasoconstriction
Spacial Resolution and Extra-cranial Contamination

- Extra-cranial contamination is the influence of surface tissues such as the scalp and skull on the rSO2 measurement of targeted tissue, such as the brain.
- Surface tissue contamination contributes to potentially inaccurate readings in certain patient conditions, such as hypothermia. *Spatial Resolution* is used in tissue oximetry to minimize or eliminate surface tissue variation.
- Tissue depth interrogated depends in part on the spacing of the optical elements.
Optimize sensor diode/detector spacing to isolate cerebral cortex

- High vascularization and metabolism
- Too shallow, extra cranial contamination
- Too deep, excludes vascular bed

### Spacial Resolution

<table>
<thead>
<tr>
<th>Extra Cerebral Tissue Thickness (mm)</th>
<th>Neonate/Infant to 6 mo</th>
<th>Ped 1 mo – 10 yr</th>
<th>Ped &gt; 40 kg 11 – 19 yr</th>
<th>Adult 20 - 60 yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skull</td>
<td>3 (1 – 5)</td>
<td>4 (3 – 6)</td>
<td>6 (5 – 8)</td>
<td>7 (5 – 12)</td>
</tr>
<tr>
<td>Scalp</td>
<td>3 (2 – 5)</td>
<td>3.5 (3 – 5)</td>
<td>4 (3 – 6)</td>
<td>4.5 (4 – 6)</td>
</tr>
<tr>
<td>Extra-cerebral TOTAL</td>
<td>6 (3 – 10)</td>
<td>7.5 (6 – 11)</td>
<td>10 (8 – 14)</td>
<td>11.5 (9 – 18)</td>
</tr>
</tbody>
</table>

Getz, 1961  
Hwang, 1999  
Strangman, 2002  
Margulies, 2000  
Young, 1959  
Adeloye, 1975
Light absorption in infant brain tissue changes during postnatal development

- Likely caused by neurologic development, myelination of axons and increased grey matter
- Spectral changes impact NIRS
- Not discrete steps at specific ages
- Approximate 10X difference between newborn and adult
Representative Validation Data

- 100 infants and children aged 8d-11 yr
- 60% neonates-<1 year
- 21% non-white
- Cyanotic and acyanotic CHD
- Arterial and jugular bulb venous samples
- \( \text{SavO}_2 = 0.7 \times \text{SvO2} + 0.3 \times \text{SaO}_2 \)
- “Accuracy” assessed by \( A_{\text{rms}} \) statistic (bias and variation) and Bland-Altman
Results

- 89% of patients ASA 3 or 4
- 62% of patients with cyanotic cardiac defects
- Room air SpO\textsubscript{2}
  - <80% in 16.5%
- <90% in 24.7% SaO\textsubscript{2}: 34-100%
- rSO\textsubscript{2}: 34-91%
- SavO\textsubscript{2}: 26-91%
- Arterial pCO\textsubscript{2} 28-61 mmHg
- Hemoglobin 8-23 g/dL
- Bilirubin 0.2-6.2 mg/ml
  - No metHgb or COHgb

What should the “lower N IRS limit” be?—Adults

- **Murkin (2007):** 75% of resting BL values
  - Anesthesia and Analgesia 2007

- **Casati (2005):** 75% of resting BL *(80% for BL <50%)* for >15 seconds
  - Anesthesia and Analgesia 2005; 740-747

- **Slater (2009):** 80% of BL
  - Annals of Thoracic Surgery 2009; 87, 36-45

- **Goldman (2006):** “at or near pre-induction BL”
  - Seminars in Cardiothoracic and Vascular Anesthesia Vol 10 No. 2, June 2006

- **Denault (2007):** 80% of BL or <50%
  - Seminars in Cardiothoracic and Vascular Anesthesia Vol 11 No. 4, December 2007

- **Mohandas B S et al (2013).** 25% of BL or <50%

- **Fischer (2011):” severe adverse outcome incidence for regional oxygen saturation thresholds of 50%..”**
NIRS—CPR (Adults)

- Ability to assess CPR efficacy, guide CPR interventions
- Ability to predict return of spontaneous circulation and outcome
Largely anecdotal reports of “efficacy” and “success” during adult CPB as well as carotid endarterectomy, DHCA, aortic aneurysm surgery, TAVR, RFCA.
Some “common desaturation causes” during CPB:

- **Mechanical**
  - Catheter position, Head position, Mechanical manipulations of the heart during off-pump
- **Carbon Dioxide**
  - Hyperventilation, Flow sweep
- **Blood Pressure**
  - Low Pump flow on by-pass
- **Low Hgb**
- **? Light anesthesia**

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Near-infrared Spectroscopy—Status of the Evidence

- Current evidence of NIRS monitoring in human studies over the past decade is consistent with class II recommendations according to the American Heart Association and the American College of Cardiology Task Force on Practice Guidelines.

- The lack of randomized, blinded, interventional trials that study the impact of NIRS along with some studies reporting equivocal outcomes associated with NIRS classifies the evidence at level B.

Multi-Site Monitoring

- Two-site cerebral and somatic NIRS monitoring measures regional oxygen delivery to the autoregulated cerebral and sympathetically mediated renal-somatic circulations.

- Under normal conditions, the renal somatic saturation (rSO2S) is approximately 10 percent greater than the cerebral saturation (rSO2C)

- A reduction in this somatic to cerebral difference (ΔrSO2SC) is associated with the development of somatic hypoperfusion and anaerobic metabolism.

  Bernal et al, Cerebral and somatic near-infrared spectroscopy in normal newborns. J Ped Surg 2010
  Hoffman et al, NIRS-derived somatic and cerebral saturation difference provides non-invasive real-time hemodynamic assessment of cardiogenic shock and risk of anaerobic metabolism. Anesthesiology 2004
Depth of signal penetration will effect the accuracy of measurement.

Gross Edema will elevate the rSO2; the more edema / 3rd spacing the higher the rSO2 [Hydrops / Profound Capillary Leak].

Ascites [fluid in the abdomen] and pneumoperitoneum [air in the abdomen] will alter signal penetration.
NIRS—DHCA (piglets)

Cerebral Oxygen Saturation-Time Threshold for Hypoxic-Ischemic Injury in Piglets

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John C. McCann, BS
Jun Wu, MD
Lili Miles, MD
Andreas W. Loepke, MD, PhD

BACKGROUND: Detection of cerebral hypoxia-ischemia (H-I) and prevention of brain injury remains problematic in critically ill neonates. Near-infrared spectroscopy (NIRS), a noninvasive bedside technology could fill this role, although NIRS cerebral O₂ saturation (S_cO₂) viability-time thresholds for brain injury have not been determined. We investigated the relationship between H-I duration at S_cO₂ 35%, a viability threshold which causes neurophysiological impairment, to neurological outcome.

METHODS: Forty-six fentanyl-midazolam anesthetized piglets were equipped with NIRS and cerebral function monitor (CFM) to record S_cO₂ and electrocortical activity (ECA). After carotid occlusion, inspired O₂ was adjusted to produce H-I (S_cO₂ 35% with decreased ECA) for 1, 2, 3, 4, 6 or 8 h in different groups, followed by survival to assess neurological outcome by behavioral and histological examination.

RESULTS: For H-I lasting 1 or 2 h, ECA and S_cO₂ during reperfusion rapidly returned to normal and neurological outcomes were normal. For H-I more than 2–3 h, ECA was significantly decreased and S_cO₂ was significantly increased during reperfusion, suggesting continued depression of tissue O₂ metabolism. As H-I increased beyond 2 h, the incidence of neurological injury increased linearly, approximately 15% per h.

CONCLUSION: A viability-time threshold for H-I injury is S_cO₂ of 35% for 2–3 h, heralded by abnormalities in NIRS and CFM during reperfusion. These findings suggest that NIRS and CFM might be used together to predict neurological outcome, and illustrate that there is a several hour window of opportunity during H-I to prevent neurological injury.

(Anesth Analg 2009;108:1268-77)
Near-infrared spectroscopy: What we know and what we need to know—A systematic review of the congenital heart disease literature

Jennifer C. Hirsch, M.D., John R. Charpie, M.D., Ph.D., Richard G. Ohye, M.D., and James G. Gurney, Ph.D.

Objectives: Neurologic dysfunction is a problem in patients with congenital heart disease. Near-infrared spectroscopy may provide a real-time window into cerebral oxygenation. Enthusiasm for near-infrared spectroscopy has increased hopes of reducing neurologic dysfunction. However, potential gains need to be evaluated relative to cost before routine implementation. Responding to data in ways that seem intuitively beneficial can be risky when the long-term impact is unknown. Thus, we performed a systematic review of the literature on near-infrared spectroscopy in congenital heart disease.

Methods: A literature search from 1950 to April 2007 for near-infrared spectroscopy in congenital heart disease was undertaken. We identified 54 manuscripts and 13 reviews.

Results: There were 47 case series, 4 randomized trials, and 3 retrospective studies. Two studies had postdischarge follow-up, one incorporating neurologic testing. Neither of these studies demonstrated a benefit. One retrospective study, which included near-infrared spectroscopy and other intraoperative measures of cerebral perfusion, demonstrated a decrease in neurologic dysfunction using this combination of monitors. Three small studies were able to correlate near-infrared spectroscopy with other clinical and radiologic findings.

Conclusions: Many centers, and even entire countries, have adopted near-infrared spectroscopy as standard of care. The available data suggest that multimodality monitoring, including near-infrared spectroscopy, may be a useful adjunct. The current literature on the use of near-infrared spectroscopy alone, however, does not demonstrate improvement in neurologic outcome. The data correlating near-infrared spectroscopy findings with indirect measures of neurologic outcome or mortality are limited. Although near-infrared spectroscopy has promise for measuring regional tissue oxygen saturation, the lack of data demonstrating improved outcomes limits the support for widespread implementation.
• Multimodal monitoring, including NIRS, MAY help prevent CNS injury
• No evidence that NIRS alone can prevent injury or improve short-term neurological outcome
• No prospective studies that relate NIRS data to direct clinical outcomes
• Very limited data that correlate NIRS values with indirect neurologic outcome measures, e.g. brain MRI or mortality
Perioperative cerebral oxygen saturation in neonates with hypoplastic left heart syndrome and childhood neurodevelopmental outcome

George M. Hoffman, MD, a, b Cheryl L. Brosig, PhD, a, b, c Kathleen A. Mussatto, BSN, PhD, a, c, d James S. Tweddell, MD, a, b, c and Nancy S. Ghanayem, MD a, b

Objectives: Neonates with hypoplastic left heart syndrome have significant hemodynamic threats to cerebral perfusion and are at risk of reduced neurodevelopmental performance. We hypothesized that cerebral hypoxia, detectable by near-infrared spectroscopy in the early postoperative period, would be related to later neurodevelopmental performance.

Methods: The study population was a sequential cohort of patients who had undergone stage 1 palliation of hypoplastic left heart syndrome under standard conditions, including neonatal perioperative monitoring with cerebral near-infrared spectroscopy, and who had undergone a neurodevelopmental assessment at age 4 to 5 years. The neonatal demographic and 48-hour perioperative hemodynamic parameters, including cerebral oxygen saturation, were tested for their relationship to 4 domains of neurodevelopmental performance, including visual-motor integration in childhood in univariate and multivariate models. The neurodevelopmental scores were classified as low if less than 85 (−1 standard deviation) and abnormal if less than 70 (−2 standard deviations).

Results: For the 51 patients in the surgical cohort, the early survival was 94%, the cumulative survival was 86%, and the neurodevelopmental assessment was completed by 21 (48%) of the survivors, without evidence of an ascertainment bias. At the test age of 56.3 ± 5.5 months, the composite neurodevelopmental index, constructed from equally weighted measures in 4 domains, was 97.6 ± 9.6, not different from the age-based norms, with 3 of 21 in the low range and none abnormal. The mean visual-motor integration was 93.4 ± 14, slightly less than the population norm (P < .05), with 2 of 21 having low scores and 1 abnormal scores. In patients with low to abnormal visual-motor integration, the perioperative stage 1 palliation cerebral oxygenation saturation was significantly lower (63.6 ± 8.1 vs 67.8 ± 8.1, P < .05). Two patients had discrete embolic strokes after their initial hospitalization; the occurrence of late stroke reduced the visual-motor integration performance but was not related to the early cerebral oxygen saturation. Nonlinear relationships of cerebral oxygen saturation to the neurodevelopmental measures found cerebral oxygen saturation thresholds of 49% to 62%. The hours at a cerebral oxygen saturation less than 45% and 55% were related to low visual-motor integration and neurodevelopmental index scores in the univariate and multivariate models. A multivariate model of age and weight at stage 1 palliation, cerebral oxygen saturation, arterial oxygen saturation, cardiopulmonary bypass and deep hypothermic circulatory arrest times, and later stroke predicted visual-motor integration to an important degree (R² = 0.53, P < .001). The actual and predicted visual-motor integration and neurodevelopmental index were normal when a cerebral oxygen saturation less than 45% and other risk conditions were avoided.

Conclusions: Neurodevelopmental performance was related to demographic, neonatal perioperative physiologic, and later factors. Perioperative cerebral oxygenation assessed by near-infrared spectroscopy can detect hypoxic-ischemic conditions associated with injury and reduced neurodevelopmental performance and was the most significant physiologic factor identified. These data suggest that efforts to avoid cerebral hypoxia are likely to improve the outcomes in this high-risk population. (J Thorac Cardiovasc Surg 2013;146:1153-64)
Problem: Only 21/56 had ND testing
2 or 3 patients/21 may have led to the conclusion of a NIRS-VMI relationship
Another Problem: patients with lower NIRS were still “normal” VMI, albeit lower end of lower normal
Predictive value of perioperative near-infrared spectroscopy for neurodevelopmental outcomes after cardiac surgery in infancy

Erica D. Sood, PhD,¹ ² Julie S. Benzaquen, PhD,¹ ² Ryan R. Davies, MD,¹ Edward Woodford, MPAS,¹ and Christian Pizarro, MD¹

Objective: The study objective was to expand on prior research examining intraoperative regional cerebral oxygen saturation (rSO₂) measured by near-infrared spectroscopy (NIRS) by evaluating the predictive value of perioperative NIRS monitoring for neurodevelopmental outcomes after infant cardiac surgery.

Methods: Cross-sectional neurodevelopmental evaluation at 24 months of age with the Bayley Scales of Infant and Toddler Development, Third Edition was performed for patients who underwent cardiac surgery with perioperative NIRS monitoring between 2007 and 2010. Retrospective clinical data were extracted from the electronic medical record. Evaluation of selected NIRS measures, including preoperative rSO₂ (baseline) as well as rSO₂ nadir and percent decrease from baseline during the intraoperative and early postoperative periods, was undertaken.

Results: Perioperative NIRS and neurodevelopmental data were available for 31 patients without chromosomal anomalies who underwent cardiac surgery during infancy at a median age of 0.43 months. Optimal thresholds on NIRS measures identified through receiver operating characteristic analyses were intraoperative percent decrease of 52% for receptive communication delay and postoperative rSO₂ nadir of 56% for cognitive delay and 49% for gross motor delay. When considered in conjunction with other clinical characteristics in stepwise linear regression analyses, intraoperative percent decrease of more than 52% entered into the final model for receptive communication outcome and postoperative rSO₂ nadir of less than 56% entered into the final model for cognitive outcome.

Conclusions: Perioperative NIRS monitoring seems to enhance the ability to predict neurodevelopmental outcome. Specific NIRS measures associated with neurodevelopmental outcome, as well as optimal thresholds, seem to differ across the continuum of the perioperative period. (J Thorac Cardiovasc Surg 2013;145:438-45)
For ND Outcome

- 31 patients total, heterogeneous, only 8 single ventricle
- 94% had DHCA
- Intraop decrease of 52% of baseline identifies 75% of children with receptive communication delay
- Postop “absolute” value <56% identifies 100% of children with cognitive delay

table3.png

TABLE 3. Univariable correlations between near-infrared spectroscopy data and neurodevelopmental outcomes

<table>
<thead>
<tr>
<th></th>
<th>Cognitive</th>
<th>Receptive communication</th>
<th>Expressive communication</th>
<th>Fine motor</th>
<th>Gross motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preoperative rSO2</td>
<td>0.31</td>
<td></td>
<td></td>
<td>0.07</td>
<td>0.14</td>
</tr>
<tr>
<td>Perioperative rSO2 nadir*</td>
<td>0.28</td>
<td>0.26</td>
<td>0.23</td>
<td>0.04</td>
<td>0.12</td>
</tr>
<tr>
<td>IO rSO2 nadir</td>
<td>0.21</td>
<td>0.29</td>
<td>0.28</td>
<td>-0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>PO rSO2 nadir</td>
<td>0.32</td>
<td></td>
<td></td>
<td>0.06</td>
<td>-0.03</td>
</tr>
<tr>
<td>Perioperative % decrease†</td>
<td>-0.29</td>
<td>-0.39§</td>
<td>-0.28</td>
<td>-0.11</td>
<td>-0.13</td>
</tr>
<tr>
<td>IO % decrease‡</td>
<td>-0.23</td>
<td>-0.44§</td>
<td>-0.37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PO % decrease</td>
<td>0.03</td>
<td>0.02</td>
<td>0.09</td>
<td>-0.02</td>
<td>-0.22</td>
</tr>
</tbody>
</table>

rSO2, Regional cerebral oxygen level; IO, intraoperative; PO, postoperative. *Refers to the lowest rSO2 over the preoperative, IO, and PO periods. †Refers to the greatest percent decrease from baseline rSO2 over the IO and PO periods. ‡Analyses exclude the 3 patients who had less than a 20% decrease from baseline rSO2 during the IO period. §P < .05. ||P < .10.
Cerebral oxygen metabolism in neonates with congenital heart disease quantified by MRI and optics


Neonatal congenital heart disease (CHD) is associated with altered cerebral hemodynamics and increased risk of brain injury. Two novel noninvasive techniques, magnetic resonance imaging (MRI) and diffuse optical and correlation spectroscopies (diffuse optical spectroscopy (DOS), diffuse correlation spectroscopy (DCS)), were employed to quantify cerebral blood flow (CBF) and oxygen metabolism (CMRO₂) of 32 anesthetized CHD neonates at rest and during hypercapnia. Cerebral venous oxygen saturation (SvO₂) and CBF were measured simultaneously with MRI in the superior sagittal sinus, yielding global oxygen extraction fraction (OEF) and global CMRO₂ in physiologic units. In addition, microvascular tissue oxygenation (StO₂) and indices of microvascular CBF (BFI) and CMRO₂ (CMRO₂) in the frontal cortex were determined by DOS/DCS. Median resting-state MRI-measured OEF, CBF, and CMRO₂ were 0.38, 9.7 mL/minute per 100 g and 0.52 mL O₂/minute per 100 g, respectively. These CBF and CMRO₂ values are lower than literature reports for healthy term neonates (which are sparse and quantified using different methods) and resemble values reported for premature infants. Comparison of MRI measurements of global SvO₂, CBF, and CMRO₂ with corresponding local DOS/DCS measurements demonstrated strong linear correlations ($R^2 = 0.69, 0.67, 0.67; P<0.001$), permitting calibration of DOS/DCS indices. The results suggest that MRI and optics offer new tools to evaluate cerebral hemodynamics and metabolism in CHD neonates.

Journal of Cerebral Blood Flow & Metabolism (2014) 34, 380–388; doi:10.1038/jcbfm.2013.214; published online 11 December 2013
Some Additional “Representative NIRS Studies

- N=250, nonrandomized, prospective study of multimodal neuromonitoring (including cerebral oximetry)
- Monitoring events strictly defined and recorded, as well as interventions prompted by the events.
- When electroencephalogram, transcranial Doppler ultrasonography, and cerebral oximetry were used together, cerebral oximetry accounted for the majority (58%) of monitoring events, with desaturation defined as a 20% reduction from baseline.
- Postoperative neurologic sequelae were detected in 26% of patients who had any monitoring event that did not provoke a response.
- Neurologic events in 6% of patients with “monitoring events”, 7% of those without monitoring events.

Austin et al J Thorac Cardiovasc Surg 1997;114:707
• N=22 MRI before and 9 days after Norwood procedure for HLHS
• 73% had new lesions, or extension of existing lesions associated with cerebral NIRS readings <45% for >180 min

• N=53 neonates pre- and postoperative MRI.
• Brain injury in 56%; low cerebral oximetry during CPB associated with new lesions.

• N=50 neonates, HLHS, postoperative to Norwood stage I repair
• Composite endpoint of ICU LOS, need for ECMO, and death as a combined outcome were associated with 48hr “mean” NIRS

Dent et al J Thorac Cardiovasc Surg 2006;131:190;
Phelps et al, Ann Thorac Surg 2009;87:1490;
McQuillen et al, Stroke 2007;38(suppl2):736
• N= 67 infants, CPB, pre- and postoperative MRI
• No association between cerebral desaturation and new neurologic injuries
• However, performed at a center that had previously embraced ‘goal-directed therapy’ CPB and other strategies of to optimize NIRS.
• Also confounded by relatively low incidence of neurologic injury in the study population (36%)
• Can’t be compared or interpreted to without randomization.

Andropoulos et al, J Thorac cardiovasc Surg 2010;139:543; Andropoulos et al 2010;139: 543
NIRS-Driven Goal Directied Therapies??

<table>
<thead>
<tr>
<th>Variable</th>
<th>Clinical scenario causing cerebral desaturation</th>
<th>Intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ delivery</td>
<td>Hypotension, elevated ICP, elevated central venous pressure</td>
<td>Maintain ABP above the lower limit of autoregulation.</td>
</tr>
<tr>
<td>CPP</td>
<td>Hypocarbia, vasospasm, malpositioned arterial cannulae</td>
<td>Check venous drainage cannula</td>
</tr>
<tr>
<td>r⁴</td>
<td>Anemia</td>
<td>Decrease minute ventilation, pH-stat management.</td>
</tr>
<tr>
<td>[Hb]</td>
<td>Cyanosis</td>
<td>Check aortic cannula position</td>
</tr>
<tr>
<td>% Sat</td>
<td>Polycythemia, sickle-cell disease</td>
<td>Transfusion</td>
</tr>
<tr>
<td>η</td>
<td>Fever, seizure, arousal</td>
<td>Lung recruitment maneuvers, increase F₁O₂, manage Qp/Qs ratio</td>
</tr>
<tr>
<td>O₂ consumption</td>
<td></td>
<td>Partial exchange transfusion, permissive anemia</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cooling, sedation</td>
</tr>
</tbody>
</table>

CPP, cerebral perfusion pressure; ICP, intracranial pressure; ABP, arterial blood pressure; r, resistance vessel radius; [Hb], blood concentration of hemoglobin; % Sat, arterial oxygen saturation; η, blood viscosity.

- Often leads to higher pump flows, permissive hypercapnia, pH-stat, increased PRBCs
- Less DHCA, more regional cerebral perfusion, more cooling
- ?? Less early extubation, increased use of inotropes
- ? Benefits ?? Harm ??increased costs


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Summary: Why is This So Hard to Figure Out? (and where do we go from here?)

- No “Class I evidence” to support NIRS as a standard of care: all of the current data is observational, unrandomized, and was not specifically designed to or actually assess ND or other outcome(s)
- Is a randomized, placebo-controlled blinded study possible at this point (“inconceivable” to many)?
- Is it necessary?
- Can it be done??
- Is it likely to work: equipoise, “background noise”, multiple axes of variability, statistical power, cost
Conclusion

- Pulse oximetry: minimal if any Class I evidence
- Cochrane review of >22,000 total perioperative patients found no evidence that pulse oximetry alters anesthetic or perioperative outcomes
- Same is true for many other commonly used monitors, e.g. ICP, apnea, in part because the monitor inevitably leads to a variety of interpretations and resultant interventions
- We probably need to continue to improve the technology and carefully and critically the changes in care prompted by it