Near-Infrared Spectroscopy (NIRS): Principles, Evidence and Clinical Applications

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What is Near Infrared Spectroscopy (NIRS)?
- NIRS can be used as a non-invasive monitoring technique for cerebral and somatic oxygenation and hemodynamics.
- Data is acquired from vascular beds (cerebral, renal, and splanchnic) with varied flows and extraction ratios.
- While pulse oximetry provides a measure of arterial oxygen saturation reflecting oxygen supply to the tissues, NIRS-measured regional oximetry measures the balance between local oxygen delivery and consumption beneath the sensor.
- It provides a non-invasive measure of end-organ oxygenation and perfusion.

NIRS Principles
- Biologic tissues absorb light in the near infrared spectrum (700-900 nm). This is called the “window into living organisms.”
- Absorption of light in the infrared spectrum is mainly by oxygenated and deoxygenated hemoglobin.
- The change in oxyHb and deoxyHb concentration can be calculated by measuring the change in absorption at 2 or more wavelengths.

How a NIRS sensor works
- Placement of NIRS sensor on Forehead. The two black circles are the light source and detector.
- Light passes from light source through the scalp, skull, and brain tissue then to the detector.
- Cerebral saturation (rSO2) reflects a ratio of arterial to venous blood of 25%-75%.

Cerebral and Somatic oximetry
- Cerebral: high-flow and high extraction compensatory mechanisms and autoregulation cerebral desaturation is a late indicator of shock if autoregulation is present
- Somatic: variable-flow, lower extraction flow is highly influenced by sympathetic tone somatic desaturation is an early indicator of shock
- Two-site NIRS can provide ongoing indications of oxygenation and perfusion changes in cerebral and somatic circulations
Regional saturation reflects oxygen balance

- rSO2 increases with more oxygen delivery or less demand while rSO2 decreases when delivery falls or rise in demand
- Oxygen delivery is influenced by:
  - Hemoglobin concentration
  - Hemoglobin saturation
  - Cardiac output (HR, preload, contractility and afterload)
  - Oxygen demand (fever, shivering, cold stress, infection, seizures, pain)
  - Oxygen demand (hypothermia, sedation/paralysis, decreased extraction

Validation of cerebral oximetry measures

**Objective:** To validate cerebral oximetry measurements with cerebral oxygen saturation directly from blood drawn from cephalad catheter in internal jugular veins in neonates on veno-venous ECMO

**Results:** There is a high level of agreement between cerebral oximetry and co-oximetry measured by jugular venous saturation.

Ras Bahrami K et al. J. Pediatr (2006)

Cerebral NIRS measures

- Regional mixed cerebral oxygen saturation (rScO2)
  \[ rScO2 = \frac{HbO_2}{HbO_2 + HHb} \]
  
  - HHb = deoxy hemoglobin
  - HbO2 = oxy hemoglobin

- Cerebral fractional tissue oxygen extraction (FTOE)
  \[ FTOE = \frac{SaO_2 - rScO_2}{SaO_2} \]
  
  - SaO2 = arterial oxygen saturation

Normal NIRS values in newborns

<table>
<thead>
<tr>
<th>rSO2</th>
<th>Term</th>
<th>Preterm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cerebral (%)</td>
<td>66-89</td>
<td>66-83</td>
</tr>
<tr>
<td>Renal (%)</td>
<td>75-97</td>
<td>64-87</td>
</tr>
<tr>
<td>Mesenteric (%)</td>
<td>63-87</td>
<td>32-66</td>
</tr>
</tbody>
</table>

Values differ by sensor type with neonatal sensors reading 10% higher


Cerebral saturation varies with gestational age and chronologic age

White - 24-25 weeks
Light gray - 26-27 weeks
Dark gray - 28-29 weeks
Black - 30-31 weeks

*Used small adult sensor with INVOS 5100 or 4100


Normal cerebral saturation during transition

Hemispheric differences in cerebral oximetry

**Purpose:** To determine if cerebral oximetry is symmetrical

**Results:** During stable and normal arterial saturations, there were only minor differences in rScO2 values.

During periods of unstable saturation, <85% and >98%, transient differences in rScO2 values of ~10% were seen between R and L.

What rScO2 values injure the brain?

- Mitochondrial damage in CA1 region of hippocampus in newborn piglets subjected to graded anoxia. Hou X et al., Physiol Meas 2007
  - rScO2 <40%

- New or worse ischemia on MRI in infants with hypoplastic left heart syndrome (HLHS). Dent C et al., J Thorac Cardi vasc Surg 2002
  - rScO2 <45% for >180 minutes

  - rScO2 ranging 33-44%

- Abnormal high energy phosphates measured by MRI spectroscopy in brains of newborn piglets. (Kusaka T, Ped Res 2009)
  - rScO2 <40%

Target rScO2 ranges for newborns

![Graph showing rScO2 ranges](image)

- **Safe zone**
- **Danger zone**

What can you do if the rScO2 is abnormal?

**If cerebral saturation is too low:**
- Hypocarbia (decrease ventilation)
- Hypotension (treat with fluid or inotropes)
- Anemia (give packed red blood cell transfusion)
- Low arterial saturation (increase FiO2)

**If cerebral saturation is too high:**
- Supranormal arterial saturation (wean FiO2)
- Hypercarbia (increase ventilation)

Two-site NIRS monitoring

- **Cerebral**
  - Sensor can be placed on right or left side of forehead

- **Renal/Flank**
  - Sensor on posterior flank below costal margin and above iliac crest (T10-L2)

Mesenteric or Splanchnic saturation monitoring

![Image of Mesenteric or Splanchnic saturation monitoring](image)
1) MacLeod D, Ikeda K, Cheng C, Shaw A. Validation of the next generation FORE-SIGHT ELITE Tissue Oximeter

Who may benefit from NIRS monitoring

- Preterm infants < 29 weeks gestation
- Infants with suspected hemodynamically significant PDA
- Hypoxic ischemic encephalopathy
- Grade III/IV intraventricular hemorrhage
- Complex Congenital heart disease
- Congenital diaphragmatic hernia
- Critically ill infants with hemodynamic instability (pre-ECMO or ECMO)

Sensor application procedure

1. Recommend place NIRS sensor onto Mepitel or other translucent skin dressing positioned. Do not apply pressure (e.g. headbands, wrap, tape).
2. Make sure signal strength bar is green
3. Check for erythema or irritation of skin around the sensor at least every 24 hours. Avoid lifting up sensor unless removing.
4. Sensor instructions state leave in place for 48 hours however we keep in place for 4-7 days.
5. Use adhesive remover or warm moist cloth to remove.

Hypocarbia during mechanical ventilation

26 4/7 weeks gestation, 925 g, chorioamnionitis, day 1 of life

HFOV can affect cerebral saturation

26 week gestation, 780 grams, on HFOV for RDS
Variable | hPDA (n=20) | No PDA (n=14) | P value
--- | --- | --- | ---
Renal saturation (%) | 61.3 | 70.3 | 0.03

Low renal saturation is associated with hPDA. Also see increased variability of tracing.

Renal saturation <66% was associated with hPDA with sensitivity of 81% and specificity of 77%, AUC = 0.786, p<0.0001.
What about the PDA in this infant?

NIRS and response to medical management of PDA

Cerebral saturation (blue) and mean blood pressure in infant with PDA being treated with indomethacin.

\( rScO_2 \) is extremely low with PDA and decreases with each dose of indomethacin.

Median \( rScO_2 \) for babies with PDA (white bars) and controls (black bars).

\( rScO_2 \) returned to normal values after treatment.

Renal saturation changes with medical management

Before Treatment: Renal sats significantly depressed at baseline with extreme variability

After Treatment: Renal sats higher with less variability

PDA and cerebral autoregulation

Cerebral autoregulation

Brain maintains constant perfusion pressure despite fluctuations in systemic blood pressure

Impaired cerebral autoregulation

Pressure passive circulation

Measured as concordance (\( r \geq 0.5 \)) between mean arterial blood pressure (MAP) and \( rSO_2 \)

- Associated with mortality, severe IVH/PVL. Tsuji et al, Pediatrics 2000

Cerebral autoregulation

Intact Autoregulation

Lack of concordance between MAP and \( rSO_2 \), \( r=0.43 \)

Impaired Autoregulation

Concordance between MAP and \( rSO_2 \), \( r=0.82 \)
PPI = Pressure Passivity Index

Average PPI in infants following PDA ligation is increased for 2 hours and then normalizes by 6 hours.

High rScO2 at 24 hours is associated with poor neurodevelopmental outcome

Use of cerebral oximetry to predict outcome in HIE

Cerebral saturation (rScO2) is higher and fractional tissue oxygen extraction (FTOE) is lower by 24 hours and onward in neonates with HIE with adverse outcomes

FTOE = SaO2 – rScO2/SaO2

High rScO2 and low FTOE reflects secondary energy failure with reduced oxygen consumption by severely injured neuronal cells

NIRS Monitoring in Congenital Heart Disease

- What can pre-operative NIRS monitoring tell us?
  - Indirect measure of Qp:Qs
    - Regardless of systemic oxygenation (SpO2), cerebral or somatic oxygenation may be inadequate
    - How do NIRS values correlate with other indicators of poor systemic perfusion (e.g., high lactate, prolonged capillary refill, cold extremities, low urine output)
  - Effectiveness or need for additional interventions
    - Ventilator changes, diuretics, change in PGE dose, need for blood transfusion, earlier surgical intervention

Infant with Juxtaductal Aortic Coarctation

SpO2 stable: 95% pre-ductal and 71% post-ductal

Cerebral sat dropped to 35-45%
PGE restarted

3-day old 31 week infant with hypoplastic left heart

SpO2 86%
SpO2 99%

Decreased UOP noted. Cr 0.6
Started Lasix and Milrinone
NIRS and Necrotizing Enterocolitis (NEC)

Splanchnic oximetry is more challenging due to marked variability in readings (16%) when compared to renal (6%), cerebral (3%) and pulse oximetry (1-2%).

Splanchnic oximetry may help identify babies with NEC. Low rsSO2 is seen with NEC and feeding intolerance as shown here. Dotted line = normal, dashed = feeding intolerance, solid = NEC.

Can NIRS monitoring improve outcomes?

Premature infants
rScO2 targets to improve outcomes
Congenital heart disease
Management of HLHS

SafeBoosC II: Phase 2 Study (Randomized)

<28 wks GA (n=166)

Infants enrolled in:
- Lyon
- Madrid
- Copenhagen
- Cork
- Utrecht
- Milan
- Graz
- Cambridge

Avoid:
- NIRS monitored
- Hyperoxia: rScO2 >85%
- Hypoxia: rScO2 <55%

Standard Treatment

Sample Size: n=86/80

What could be done?

When cerebral rScO2 is low (<55%), consider:
- Low pCO2 (Increase pCO2)
- hspDA (Close)
- Hypotension (treat)
- Anemia (Erytrocyte transfusion)
- Low arterial saturation (Increase FiO2)

When cerebral rScO2 is high (>85%), please consider:
- Supranormal Art Sat (Decrease FiO2 if possible)
- Too high pCO2 (Decrease pCO2)
- Low glucose (Treat low blood glucose)

Use of NIRS in pre-op newborns with HLHS

Hypothesis: Pre-operative use of NIRS would reduce the need for invasive therapies including controlled ventilation and inspired gas manipulation

Methods: Retrospective review of infants who had stage I palliation for HLHS from 2000-2006

Historical cohort from 2000-2002 without pre-op NIRS monitoring (n=47)

NIRS cohort from 2003-2006 had cerebral and somatic NIRS measures recorded hourly (n=45)
## NIRS in HLHS - Results

<table>
<thead>
<tr>
<th></th>
<th>Control (n=47)</th>
<th>NIRS (n=45)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intubated, n (%)</td>
<td>39 (83)</td>
<td>27 (60)</td>
<td>0.014</td>
</tr>
<tr>
<td>Inspired nitrogen, n (%)</td>
<td>33 (70)</td>
<td>7 (16)</td>
<td>0.001</td>
</tr>
<tr>
<td>Duration nitrogeneuse, hours</td>
<td>39.3</td>
<td>30.30</td>
<td>0.001</td>
</tr>
<tr>
<td>Arterial saturation (%)</td>
<td>87.6</td>
<td>91.9</td>
<td>0.001</td>
</tr>
<tr>
<td>Cerebral saturation (%)</td>
<td>68.0</td>
<td>68.05</td>
<td></td>
</tr>
<tr>
<td>Somatic saturation (%)</td>
<td>70.3</td>
<td>70.35</td>
<td></td>
</tr>
</tbody>
</table>

Higher systemic saturation in NIRS monitored group was not associated with hypotension, acidosis, or worsened renal function.

## NIRS in HLHS - Conclusions

Routine use of pre-op NIRS-monitoring resulted in:
- Reduced mechanical ventilation (higher SaO₂, lower PaCO₂)
- Reduced use of inspired gases
- No impact on mortality or length of hospital stay

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## Conclusions

- NIRS monitoring is a useful non-invasive measure of endorgan oxygenation and perfusion providing critical information about the balance of oxygen delivery and consumption.
- While there are wide ranges on normal values in newborns depending on the device and sensor used, trend monitoring provides critical information in specific clinical scenarios.
- Further studies are needed to determine if NIRS can improve important patient outcomes in newborn infants.

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Thank you!