Optimizing Unanesthetized Cerebral Oxygen Consumption Measures: Comparison of NIRS and MRI Approaches in Neonates with Congenital Heart Disease

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Optimizing Unanesthetized Cerebral Oxygen Consumption Measures: Comparison of NIRS and MRI Approaches in Neonates with Congenital Heart Disease

Silvana F. Ferradal¹, Jeffrey N. Stout², Borjan Gagoski¹, Rutvi Vyas¹, Christopher Ha¹, Divya S. Bolar³,⁴, Henry H. Cheng⁵, Jane Newburger⁵, Maria A. Franceschini⁶, Elfad Aladalsteinson⁷,⁸ and P. Ellen Grant¹

¹Fetal-Neonatal Neuroimaging and Developmental Science Center, Boston Children’s Hospital, Boston, MA, United States
²Harvard-MIT Health Sciences and Technology, Massachusetts Institute of Technology, Cambridge, MA, United States
³Martinos Center for Biomedical Imaging, MGH/Harvard Medical School, Boston, MA, United States
⁴Department of Radiology, Massachusetts General Hospital, Boston, MA, United States
⁵Department of Cardiology, Boston Children’s Hospital, Boston, MA, United States
⁶Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA, United States
⁷Institute for Medical Engineering and Science, Cambridge, MA, United States
silvina.ferradal@childrens.harvard.edu

Abstract: Cerebral perfusion in neonates with congenital heart disease is a clinical concern. Combined measures of MRI and NIRS can provide complementary information to improve monitoring. We compare multimodal measures of cerebral hemodynamics in this group.

OCIS codes: (300.6340) Spectroscopy, infrared; (170.2655) Functional monitoring and imaging; (170.0110) Imaging systems

1. Introduction

Moderate to severe congenital heart disease (CHD) affects 6/1000 live births, with severe CHD resulting in adverse neurodevelopmental outcomes in over 50% (1). The etiology of neurodevelopmental disorders is unknown but evaluation of the hemodynamic state of CHD infants pre- and post-surgically has become a focus with cerebral metabolic rate of oxygen consumption (CMRO₂) identified as a key parameter for clinical evaluation (2-5). Jain et al. (4) demonstrated correlations between magnetic resonance imaging (MRI) and near-infrared spectroscopy (NIRS) measures of CMRO₂ pre-surgically when measured simultaneously in anesthetized neonates. We present NIRS and MRI-based measures of cerebral hemodynamics (OEF, CBF and CMRO₂) in nine stable neonates with CHD. NIRS and MRI measures were performed without anesthesia and within one day from each other. Measures obtained with both modalities are compared to literature values.

2. Methods

Subjects: Nine infants (age=4.8±2.5 days) were recruited at Boston Children’s Hospital after IRB approval and parental consent. MRI and NIRS measurements took place in the pre-operative period.

Data acquisition: Frequency-domain NIRS (FD-NIRS) and diffuse correlation spectroscopy (DCS) systems were used for the optical measurements (6). The FD-NIRS system has two banks of laser diode sources operating at 8 wavelengths (667-825nm) and two PMT detectors. The sources are modulated at 110 MHz, and the detectors at 110 MHz + 5 kHz for heterodyne detection at 5 kHz. The DCS system has a long coherence length laser source (785 nm) and four APD detectors. An eight-channel correlator is converts the detected light at each DCS channel into temporal intensity autocorrelation functions. Absorption (μₐ) and scattering (μₛ) coefficients were measured with FD-NIRS. Oxygenated (HbO₂) and deoxygenated (HbR) hemoglobin were derived from the absorption coefficients using hemoglobin extinction coefficients reported in the literature. Cerebral oxygen saturation was computed as SO₂ = HbO₂/(HbO₂+HbR). For DCS, each measured intensity autocorrelation function was fit to obtain a blood flow index (CBF) using the semi-infinite solution to the correlation diffusion equation for a homogenous medium (6, 7). Individual μₐ and μₛ at 785 nm were used in the fitting. The MRI protocol included: Structural MEMPRAGE; time of flight angiogram (MRA) positioned to include the circle of Willis and the neck; velocity encoded phase contrast image positioned manually based on the MRA perpendicular to the basilar artery and inferior carotid arteries (TE/TR=4.67/16.65ms, resolution=0.5x0.5x4.0mm, velocity encoding=100cm/s); T-relaxation under spin tagging (TRUST) positioned 15 mm above the confluence of the sinuses perpendicular to the superior sagittal sinus (TE/TR=15/5000ms, resolution=2.3x2.3x5mm, inversion time=1025ms, tagging width=50mm, tagging gap=15mm) (8). Venous oxygen saturation (SvO₂) was calculated from T₂ using a published calibration (9).

Measurements of brain metabolism: Oxygen extraction fraction was computed as OEF = (SaO₂-SvO₂)/SvO₂, where SaO₂ was measured with a pulse oximeter. Cerebral metabolic rate of oxygen consumption was computed as
CMRO$_2$ = 1.39 × $\text{SaO}_2$ × [Hb] × CBF × OEF, where [Hb] is the hemoglobin concentration measured from blood samples.

3. Results

Figures 1 and 2 show CMRO$_2$ comparisons between our results and the literature. Figure 3 shows the correlation between SvO$_2$ and OEF measured by FD-NIRS and MRI.

4. Discussion

Compared to previous studies, our FD-NIRS/DCS results show decreased CMRO$_2$ in CHD relative to controls (10), but higher CMRO$_2$ than anesthetized subjects (4) (Figure 1). A similar trend is observed with our MRI results, showing a decreased CMRO$_2$ relative to healthy subjects examined with a similar technique (8), and slightly higher CMRO$_2$ than in anesthetized subjects (4, 11) (Figure 2). SvO$_2$ and OEF measurements correlate across modalities ($r^2=0.596$, $p=0.015$ for SvO$_2$; $r^2=0.525$, $p=0.027$ for OEF) suggesting that these measures capture similar information and/or are relatively stable in this cohort (Figure 3). However, there was no significant correlation between DCS and MRI measurements of CBF. Several possibilities could explain the discrepancy: 1. Measurements were not performed simultaneously and subjects with CHD have fluctuating physiology even when stable. 2. Sample size was limited as neonates needed to be stable and asleep to have a successful MRI scan. 3. MRI and NIRS rely on different models and assumptions that could lead to different measurement biases. We studied stable preoperative neonates without anesthesia and although the sample size was small the results compare well to other within modality measures (Figures 1, 2). Thus, we suspect the discrepancy between modalities is due to different biases, particularly in CBF measures, which have a direct effect on CMRO$_2$. MRI CBF measurements are based on large cerebral artery blood volume inflow, whereas NIRS measurements are based on microvascular red blood cells (RBC) flow.

5. Conclusions

MRI and NIRS provide complementary methods for quantification of cerebral hemodynamics that if cross-validated would increase our confidence in both modalities and lead to more comprehensive bedside clinical monitoring. However, before data between these two modalities can be compared or combined, additional studies are needed to better understand the relationship between large vessel bulk flow and microvascular RBC flow. SvO$_2$ and OEF measurements in our study are significantly correlated between modalities, but CBF, and therefore CMRO$_2$, are not in good agreement either due to differences in physiology or biases in these measurements.

**Figure 1**: Index of cerebral metabolic rate of oxygen consumption (CMRO$_2$) measured with FD-NIRS/DCS. CMRO$_2$ values are shown as median and interquartile ranges.

**Figure 2**: MRI-based CMRO$_2$ comparison between this study and values reported in the literature. CMRO$_2$ values are shown as mean and standard deviation.
Figure 3: Significant correlations were obtained between FD-NIRS and MRI measurements of SvO$_2$ and OEF, respectively. A linear regression model was estimated for each variable (the red solid line represents the best fit, while the dashed lines represent 95% confidence bounds).

References


