

Use of Near-Infrared Spectroscopy for Estimation of Renal Oxygenation in Children With Heart Disease

Laura A. Ortmann · Eudice E. Fontenot ·
Paul M. Seib · Brian K. Eble · Ross Brown ·
Adnan T. Bhutta

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Abstract We evaluated whether near-infrared spectroscopy (NIRS) measurement from the flank correlates with renal vein saturation in children undergoing cardiac catheterization. Thirty-seven patients <18 years of age were studied. A NIRS sensor was placed on the flank, and venous oxygen saturations were measured from the renal vein and the inferior vena cava (IVC). There was a strong correlation between flank NIRS values (rSO_2) and renal vein saturation ($r = 0.821$, $p = 0.002$) and IVC saturation ($r = 0.638$, $p = 0.004$) in children weighing ≤ 10 kg. In children weighing > 10 kg, there was no correlation between rSO_2 and renal vein saturation ($r = 0.158$, $p = 0.57$) or IVC saturation ($r = -0.107$, $p = 0.67$). Regional tissue oxygenation as measured by flank NIRS correlates well with both renal vein and IVC oxygen saturations in children weighing < 10 kg undergoing cardiac catheterization, but not in larger children.

Keywords Near-infrared spectroscopy · NIRS · Renal oxygenation · Renal failure

Introduction

Near-infrared spectroscopy (NIRS) is a noninvasive technology that uses the different absorption spectra of

oxy-hemoglobin and deoxy-hemoglobin to provide a continuous estimate of regional tissue oxygen saturation (rSO_2). The most common clinical application of this technology has been in assessing cerebral oxygen saturation with a probe placed on the forehead. Studies have shown a correlation between cerebral oxygenation as measured by NIRS and jugular venous, central, and mixed venous saturations [5, 13, 14, 16, 23].

Due to cerebral autoregulation, blood flow and oxygen delivery to the brain may be preserved in low cardiac output states. Thus, cerebral NIRS values may not represent perfusion to other organs during low cardiac output. This has led to NIRS technology being employed at multiple different sites [8, 20, 22].

NIRS monitors are now being widely used to monitor renal perfusion with a probe placed on the flank, especially in pediatric cardiac intensive care units because children undergoing cardiac surgery are at increased risk for acute renal failure due to decreased perfusion and oxygen delivery in the intraoperative and postoperative periods [1, 6, 12, 24]. Preliminary evidence presented by Hoffmann et al. suggest that renal NIRS values in this group are associated with regional ischemia and changes in kidney function [10, 11]. Although flank rSO_2 has been found to weakly correlate with superior vena cava saturations in infants [14, 15], there are no published studies investigating whether these readings actually correlate with renal vein saturations.

The purpose of this study was to evaluate whether NIRS measurements from the flank correlate with renal vein saturations in children. Inferior vena cava (IVC) oxygen saturations were also measured and compared with NIRS because saturations from this location have been used as an indicator of global perfusion [9].

L. A. Ortmann (✉) · R. Brown · A. T. Bhutta
Division of Critical Care, Department of Pediatrics,
University of Arkansas for Medical Sciences,
Little Rock, AR, USA
e-mail: lortmann@stanford.edu

E. E. Fontenot · P. M. Seib · B. K. Eble · A. T. Bhutta
Division of Cardiology, Department of Pediatrics,
Arkansas Children's Hospital, Little Rock, AR 72202, USA

Materials and Methods

Study Population

Pediatric patients <18 years of age undergoing medically indicated cardiac catheterization at Arkansas Children's Hospital were eligible for participation in this study. This study was approved by the Institutional Review Board at the University of Arkansas for Medical Sciences. Written informed consent was obtained from the legal guardians and assent from subjects >7 years.

Data Collection

In the catheterization laboratory, a NIRS probe (INVOS Cerebral/Somatic Oximeter 5100B; Somanetics Inc., Troy, MI) appropriate for weight was placed at the T10 to L2 level lateral to midline by the principal investigator before the start of the procedure. The cerebral oximeter used in this study uses NIRS technology to measure regional changes in oxygenated and deoxygenated hemoglobin in the tissue under the probe. The probe emits two different wavelengths of near-infrared light (730 and 810 nm), which correspond to the different spectral absorptions of oxygenated and deoxygenated hemoglobin. Measuring the quantity of returning light of each wavelength allows for assessment of changes in the concentrations of these molecules.

Vessel cannulation and timing of blood samples were at the discretion of the cardiologist performing the procedure. Inspired oxygen percentage delivered was based on the clinical needs of the patient. Blood samples were drawn from the left or right renal vein and the IVC below the diaphragm, but superior to the renal vein, with an end-hole catheter placed under fluoroscopic guidance. We recorded rSO₂ at the time of blood sample collection. Oxygen saturations and hemoglobin level were obtained immediately after drawing the samples with a GEM OPL portable laboratory co-oximeter (Instrumentation Laboratory, Lexington, MA). Additional data collected included age, sex, diagnoses, weight, height, pulse oximetry, cardiac index as measured by Fick, and inspired oxygen percentage.

Statistical Analysis

Descriptive statistics were performed on demographic data. Subjects weighing ≤10 kg and those weighing >10 kg were analyzed separately to evaluate the effect of weight on rSO₂ correlations. We compared the rSO₂ values and measured venous saturations using concordance correlation coefficients, which evaluate the degree to which pairs of observations fall on the 45° line through the origin. Pearson's correlation coefficients (a measure of precision) and

bias correction factors (a measure of accuracy) were also calculated. Bland-Altman plots, which illustrate the difference versus the average of the two methods, were used to estimate the precision and bias of the study variables.

Results

Forty children were consented for study; 19 weighed ≤10 kg, and 21 weighed >10 kg. Data were not collected on 1 patient (>10 kg) due to respiratory compromise before the procedure and 2 patients (1 ≤10 kg and 1 >10 kg) who did not have blood samples drawn by the physician performing the catheterization. Mean weight was 6.2 kg (range 2.2 to 10) for subjects ≤10 kg and 18.8 kg (range 10.4 to 67) for subjects >10 kg. Mean age was 4.8 months (range 3 days to 20 months) for subjects ≤10 kg and 83 months (range 18 to 163) for subjects >10 kg. Renal vein saturations were not measured in 7 of the children weighing ≤10 kg and 4 of the children weighing >10 kg due to difficulties accessing the renal vein from the superior vena cava approach or hemodynamic instability before renal vein cannulation. Seven subjects (19%) had cyanotic heart disease with a baseline arterial saturation of <90%.

Saturations and rSO₂ values for subjects weighing ≤10 kg and those weighing >10 kg are listed in Tables 1 and 2, respectively. Using Pearson's correlation, we found a significant correlation between flank rSO₂ and renal vein saturation ($r = 0.821$, $p = 0.002$) and between rSO₂ and IVC saturation ($r = 0.638$, $p = 0.004$) in children ≤10 kg. Concordance correlation coefficient was 0.77 for rSO₂ and renal vein saturation and 0.63 for rSO₂ and IVC saturation. Bias correction factor was 0.94 for renal vein saturations and 0.99 for IVC saturations.

In children weighing >10 kg, there was no correlation between rSO₂ and renal vein saturation ($r = 0.158$, $p = 0.57$) or IVC saturation ($r = -0.107$, $p = 0.67$). The concordance correlation coefficient was also low at 0.15 for rSO₂ and renal vein saturation and -0.07 for rSO₂ and IVC saturation. Bias correction factor was 0.94 for renal vein saturations and 0.7 for IVC saturations in children weighing >10 kg. Bland-Altman plots demonstrating the bias and precision of these measurements are shown in Fig. 1.

Discussion

Our study clearly indicates that there is a significant correlation between rSO₂ as measured by flank NIRS and renal vein saturation in children weighing <10 kg. There is also a good correlation between rSO₂ and IVC saturation.

Table 1 Saturation data for subjects weighing ≤ 10 kg

Case no.	Weight (kg)	Diagnosis	Pulse oximetry	IVC saturation	rSO ₂ at time of IVC saturation	Renal vein saturation	rSO ₂ at time of renal vein saturation
1	2.2	Pulmonary atresia	88	58	49		
2	3.8	HLHS post-Norwood	81	50	49	44	47
3	4.4	Pulmonary stenosis	97	79	83	76	89
4	3.4	Pulmonary stenosis	98	70	71	53	54
5	4.3	Heart transplant	98	59	64	63	64
6	10	Heart transplant	98	72	81		
7	7.8	HLHS pre-Glenn	77	53	66		
8	6	Double-outlet right ventricle post-repair	97	66	45		
9	9	Pulmonary stenosis	98	66	70	72	70
10	6.5	TOF post-repair, pulmonary stenosis	100	90	95	87	95
11	8	AVC post-repair	98	75	78		
12	6	Heart transplant	98	41	67		
13	7	TOF/pulmonary atresia	96	57	68	65	80
14	7.8	Pulmonary stenosis	99	79	74	79	75
15	5.6	HLHS pre-Glenn	77	65	60	62	60
16	5.5	Truncus arteriosus	95	69	62		
17	6.6	Heart transplant	98	67	56	66	56
18	7.5	Heart transplant	98	69	76	59	76

HLHS hypoplastic left heart syndrome, TOF tetralogy of Fallot, AVC atrioventricular canal

Table 2 Saturation data for subjects weighing > 10 kg

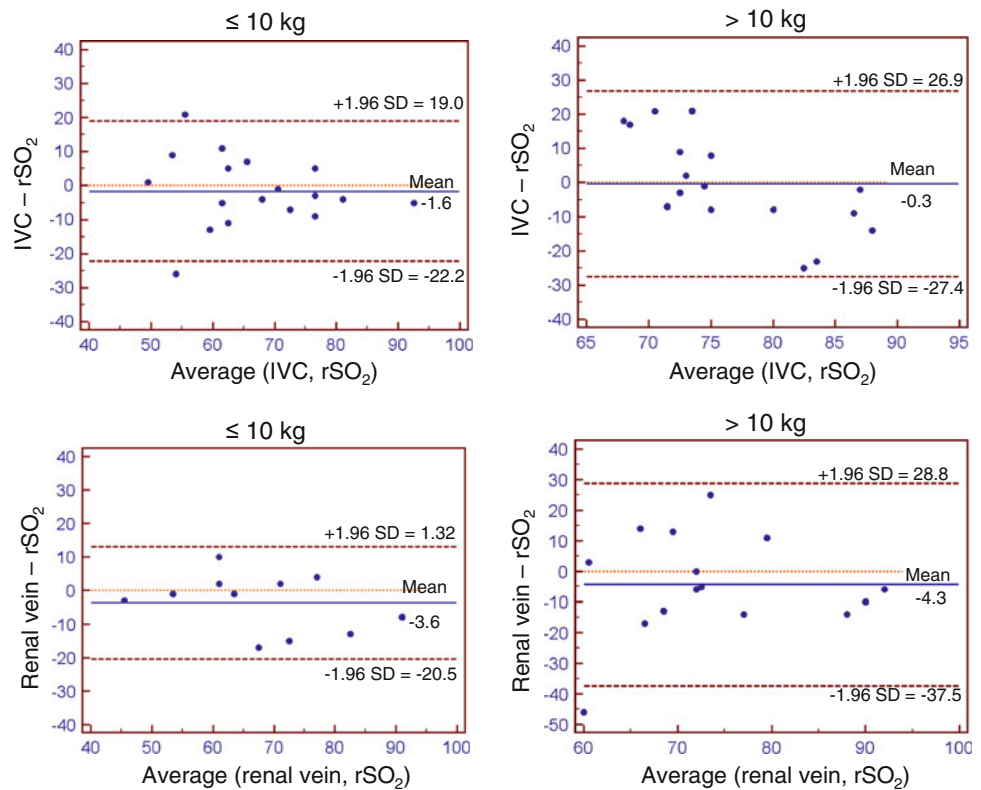
Case no.	Weight (kg)	Diagnosis	Pulse oximetry	IVC saturation	rSO ₂ at time of IVC saturation	Renal vein saturation	rSO ₂ at time of renal vein saturation
1	20	Heart transplant	98	84	63	76	63
2	21	Heart transplant	98	79	71	85	74
3	18	Heart transplant	97	77	60		
4	12	Pulmonary stenosis	99	82	91		
5	13	Double-outlet left ventricle post-Glenn	89	81	95	81	95
6	20	Pulmonary atresia, post-two-ventricle repair	96	81	60	76	59
7	14	ASD	96	71	79	37	83
8	61	ASD	96	71	74	58	75
9	31	ASD	95	72	95	85	95
10	24	Heart transplant	98	77	59	62	59
11	14	HLHS pre-Fontan	83	74	72	72	72
12	16	Truncus arteriosus post-repair	100	70	95	89	95
13	47	Pulmonary stenosis	99	74	75	70	75
14	33	VSD	99	77	68		
15	15	PDA	100	86			
16	17	Left pulmonary artery stenosis	98	74	75	62	75
17	18	Left pulmonary artery stenosis	99	76	84	70	84
18	30	Heart transplant	98			86	61
19	12	HLHS pre-Fontan	80	68	75	69	75

HLHS hypoplastic left heart syndrome, TOF tetralogy of Fallot, AVC atrioventricular canal, PDA patent ductus arteriosus

The NIRS measurements were noted to be both precise and accurate in this group. There was no correlation between the measured renal vein and IVC saturations and the flank

rSO₂ in children > 10 kg. Among this group rSO₂ was a low precision but highly accurate estimate of renal vein saturation, as can be seen in the Bland-Altman plots.

Fig. 1 Bland-Altman plots of the difference between rSO₂ and measured venous saturations versus the average of rSO₂ and measured venous saturations for children weighing ≤10 kg and those weighing >10 kg. Mean difference and limits of agreement are noted



Children undergoing repair of congenital heart disease are at high risk of developing acute renal failure with the incidence of postoperative dialysis varying from 2.3% to >30% [3, 18, 23]. Children who develop renal failure after surgery are at much greater risk of mortality [3, 6]. Although the mechanisms for renal failure after cardiac surgery are multifactorial, diminished renal perfusion secondary to decreased myocardial function and hypotension leading to ischemic tubular necrosis is thought to be the main contributor.

The kidney receives a disproportionately high fraction of the cardiac output compared with its metabolic need; however, the local mechanisms that balance oxygen delivery and use and low oxygen tension in the outer medulla put the kidney at risk for hypoxic injury [7]. Late indicators, such as oliguria and increased creatinine, are used to assess renal perfusion but are limited because renal injury has already occurred by the time these clinical changes are noted. NIRS may provide an accurate, noninvasive, real-time measure of renal oxygenation. Interventions to correct the oxygen supply–demand balance could potentially decrease the incidence of renal dysfunction in patients at risk for decreased renal perfusion.

Few studies have reported on flank NIRS values and actual patient clinical outcomes. In children undergoing repair of coarctation of the aorta, cross-clamping of the aorta was accompanied by a large decrease in somatic

oxygenation [4]. Owens et al. studied somatic oxygenation as measured by flank NIRS in infants undergoing biventricular repair [17]. NIRS values <50% for >2 h after surgery were predictive of increased creatinine and a greater incidence of acute kidney injury by 48 h. They also found that those with low flank NIRS had worse clinical outcomes, including increased lactate, more ventilator days, and greater vasoactive medication need.

Most studies using NIRS have focused on measurements of regional cerebral oxygenation, but clinicians should use caution in applying these studies to NIRS use in other locations. Oxygen use and control of blood flow differ remarkably in different body tissues. In a study using both cerebral and flank NIRS, Hanson et al. saw a significant increase in somatic NIRS values with fluid resuscitation in moderately dehydrated patients [9]. Cerebral NIRS values were greater at baseline and did not change during rehydration. During times of decreased cardiac output, sympathetic vasoconstriction will shunt blood away from vascular beds, such as mesenteric, renal, and cutaneous, to preserve blood flow to the brain. Thus, decreased somatic NIRS in the context of normal cerebral NIRS may give an earlier indication of impaired output.

Our study found a correlation between flank NIRS measurements and IVC saturations in children weighing <10 kg. Use of IVC saturation as a measure of oxygen delivery to the tissues is often performed in the intensive

care unit given the technical difficulties that can be present in obtaining superior vena cava or mixed venous saturations in infants [19]. The IVC receives blood from multiple tissue beds and reflects perfusion to the lower body, and NIRS measurements from the thigh have also been correlated to IVC saturations [21]. This study suggests that the flank NIRS probe can also be helpful in assessing global perfusion noninvasively.

The difference in correlations between smaller and larger children is not unexpected given the limited sampling depth of the NIRS probe. According to the manufacturer, the NIRS readings compared with somatic tissue are reflective of oxygenation approximately 1 to 2 cm beneath the sensor (<http://www.somanetics.com/our-technology/nirs-technology>). Balaguru et al. measured the body wall thickness of 38 children undergoing computed tomography scans [2]. The median distance between the skin and the capsule of the kidney was 22 mm and had a wide range (6.6 to 116). As expected, this distance increased with increasing age and weight. The infrared light emitted from the NIRS probe likely did not penetrate beyond the subcutaneous tissues in our larger patients. In small children, the body wall is presumably thin enough to allow the infrared light to reach the kidney parenchyma. Using weight instead of body mass index (BMI) is a limitation of our study because BMI may provide a better indication of body wall thickness than weight. High BMI was uncommon in this patient population, so a larger sample size would be needed to stratify patients by BMI.

Although flank measurements in children weighing <10 kg correlated with IVC saturations, this was not the case in the larger children, suggesting that use of a flank probe may be limited in its utility in this population. However, NIRS and saturation measurements in this study were made at a single time point, and NIRS is often clinically used to assess changes in hemodynamics over time. A probe at this location may still be useful as an indicator of tissue perfusion trends.

In conclusion, regional tissue oxygenation measured by flank NIRS correlates well with both renal vein and IVC oxygen saturations in children weighing <10 kg who are undergoing cardiac catheterization. There is no correlation between measured venous saturations and NIRS values over the flank in children weighing >10 kg. Further investigation is needed to assess how measurement of flank NIRS values are correlated with renal function and whether interventions aimed at improving perfusion and NIRS values results in less kidney injury and improved outcomes.

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