

Regional and central venous oxygen saturation monitoring following pediatric cardiac surgery: Concordance and association with clinical variables*

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Objective: To compare changes in regional cerebral or flank oxygen saturation measured by near-infrared spectroscopy with changes in central venous oxygen saturation (Scvo₂) and to determine clinical variables associated with these changes.

Design: Prospective observational cohort study.

Setting: University tertiary care center, pediatric cardiac intensive care unit.

Patients: Seventy postoperative congenital cardiac surgical patients (median age 0.3 yrs; interquartile range 0.02–0.46 yrs).

Interventions: None.

Measurements and Main Results: We measured temporally correlated regional oxygen saturation (rSo₂) with hematologic (hematocrit), biochemical (arterial blood gas, Scvo₂, and lactate) and physiologic (temperature, heart rate, mean blood pressure, and pulse oximetry) variables in the first postoperative day. Cerebral and flank rSo₂ were strongly correlated with Scvo₂, in both cyanotic or acyanotic patients and single- or two-ventricle physiology with and without aortic arch obstruction (all $p < .001$). However, individual values had wide limits of agreement on Bland-Altman analysis. The

correlations of change in these measurements were weaker but still significant (all $p < .0001$), again with wide limits of agreement. Similar direction of change in cerebral rSo₂ and Scvo₂ was present 64% (95% confidence interval, 55–73%) of the time. Change in arterial pressure of carbon dioxide (Δ Paco₂) was associated with cerebral Δ rSo₂ (Δ Paco₂ $\beta = 0.35$, $p < .0001$) but not flank Δ rSo₂ or Δ Scvo₂. A pattern of relative cerebral desaturation (flank rSo₂ > cerebral rSo₂) was noted in a majority of patients (81%) with two-site monitoring regardless of bypass method or age.

Conclusions: Neither individual values nor changes in rSo₂ are interchangeable measures of Scvo₂ in postoperative pediatric cardiac patients. The unique relationship between changes in Paco₂ and cerebral rSo₂ supports the hypothesis that cerebral near-infrared spectroscopy monitors regional cerebral oxygenation. Clinical application of this monitor must include recognition of the clinical variables that affect regional brain oxygenation. (Pediatr Crit Care Med 2007; 8:154–160)

KEY WORDS: near-infrared spectroscopy; pediatric intensive care units; thoracic surgery; brain; autoregulation; cardiac output

Cerebral hemoglobin oxygen saturation measured with near-infrared spectroscopy (NIRS) is used to monitor and titrate brain oxygen delivery during cardiopulmonary bypass with regional cerebral perfusion (1–3) and during repair of aortic coarctation without bypass (4). Cerebral oxygen saturation monitoring is increasingly employed preoperatively (5)

and postoperatively in the pediatric cardiac intensive care unit (PCICU), where it has been advocated as a surrogate measure of central venous oxygen saturation (Scvo₂) (6, 7), an important variable used to assess adequacy of oxygen delivery and consumption (8).

Initial studies of this application have determined that regional cerebral and central venous oxygen saturation are

strongly correlated but individual values are not interchangeable (wide limits of agreement) (6, 7, 9), leading to speculation that regional cerebral oxygen saturation monitoring might be more suitable to monitor trends in Scvo₂. However, cerebral blood flow is intrinsically regulated by physiologic variables including arterial blood pressure and Paco₂ (10). If these autoregulatory systems are intact, a change in cerebral blood flow may occur independently of a change in systemic oxygen delivery. A better understanding of the indications for and information provided by cerebral NIRS monitoring following cardiac surgery for congenital heart disease is needed.

This study had two specific objectives: a) to evaluate the relationship of change in cerebral regional oxygen saturation with change in regional flank and central

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venous oxygen saturation with the hypothesis that trends in these variables are related; and b) to determine the physiologic, hematologic, and biochemical variables associated with changes in cerebral, flank, and central venous oxygen saturation, with the hypothesis that cerebral oxygen saturation should be differentially affected by variables known to influence cerebral blood flow.

METHODS

Patients. Between December 2004 and August 2005, we prospectively studied 70 consecutive patients, including three adult patients (age = 21, 32, 34 yrs), admitted to the PCICU following cardiac surgery for congenital heart disease. Patients were included if a clinical decision was made to continue the routine monitoring of regional oxygen saturation initiated in the operating room. Patients were studied with waiver of voluntary, informed parental consent as no intervention was undertaken and all data were stripped of identifiers that might compromise confidentiality of private healthcare information. The University of California, San Francisco, Committee on Human Research approved the study protocol. Given the study design, neurodevelopmental outcome assessment was not performed.

Regional Oxygen Saturation Monitoring. An INVOS 5100 Cerebral Oximeter (Somanetics, Troy, MI) is routinely employed to monitor pediatric cardiac surgery patients during cardiopulmonary bypass in our institution. The INVOS 5100 offers the capability of single- or dual-site monitoring with an adult (>40 kg) or pediatric (<40 kg) disposable Somasensor. The INVOS 5100 emits near-infrared light at two wavelengths (730 and 805 nm) and employs two detectors and spatially resolved spectroscopy to measure light absorption due to chromophores (oxyhemoglobin and deoxyhemoglobin) in the brain and not overlying skin and skull. Using a proprietary calculation, the ratio of oxyhemoglobin to deoxyhemoglobin is expressed as regional oxygen saturation (rSo₂). Following induction of anesthesia, a Somasensor is placed over the skin of the left forehead below the hairline. In patients ≤3 months old (n = 29), at the discretion of the operating room team, a second sensor is placed on the flank. The Somasensors are left in place following cardiac surgery, and monitoring is resumed after transport to the PCICU. Postoperative monitoring is continued at the discretion of the clinical team in the PCICU. Generally, monitors are left in place for the first postoperative day, unless the patient is extubated before that time.

Data Collection. Postoperative data were prospectively collected from the medical records by a study investigator and included patient demographic and procedural variables as well as a defined set of laboratory results and physiologic variables. Specifically, at the

end of each recording, the cardiac intensive care unit flow sheet was examined for ScvO₂, serum lactate, hematocrit, or change (Δ) in the following variables: ΔPaco₂ >5 torr, Δ temperature >2°C, Δ mean arterial pressure (MAP) >10 mm Hg. Each event is defined by a pair of event times. In the case of laboratory data (ScvO₂, lactate, Paco₂, or hematocrit), the event times were determined by when each blood sample was drawn. In the case of a physiologic change (temperature, MAP), the event times were determined by time from peak to trough as charted on the nursing flow sheet. Data were recorded along with a complete set of physiologic data (heart rate, MAP, systemic arterial oxygen saturation by pulse saturation [Sao₂], temperature) or laboratory data (arterial blood gas, hematocrit, ScvO₂, and lactate), allowing for the comparison of a broad range of changes in all physiologic variables in addition to the predefined events of sufficient magnitude. A continuous recording of rSo₂ was initiated by the patient's nurse and was maintained until NIRS monitoring was discontinued. Event times from the patient flow sheet were used to extract rSo₂ values from the continuous recordings at the appropriate times. Central venous blood is routinely sampled from a variety of sources: transthoracic or percutaneous catheters in the right atrium, superior, or inferior vena cava. Central venous blood gases were not coded by catheter type or tip location.

Data Analysis. Clinical variables were entered into a relational database (Filemaker Pro 7) and exported for statistical calculations with Stata 8 software (Stata Corporation, College Station, TX). Spearman's rank correlation determined association between individual rSo₂ and ScvO₂ values and between changes in those values (ΔrSo₂ and ΔScvO₂). Bland-Altman analysis was used to determine the mean difference and 95% limits of agreement between cerebral and central venous satura-

tion (11). The association between changes in laboratory and physiologic variables and ΔrSo₂ and ΔScvO₂ was determined with univariate regression analysis for repeated measures (generalized estimating equation). Kruskal-Wallis was used to test for association between categorical and continuous variables. Fisher's exact test was used to determine association between categorical variables. Significant associations for the entire cohort were explored across subgroups of patients representing functional anatomical groups based on the number of functional ventricles and the presence of aortic arch obstruction (12), cyanotic cardiac physiology, and age <1 yr.

RESULTS

Patient Characteristics and Clinical Measurements. Seventy patients with a median age of 0.3 yrs and weight of 4.6 kg were studied from December 17, 2004, to August 12, 2005. Table 1 summarizes the patients' demographics and clinical variables. The patients represented a broad selection of congenital heart disease with diagnosis summarized by cardiac anatomical group in Table 2. There were no differences in the demographic characteristics across cardiac anatomical groups (all *p* > .3). The majority of patients were <1 yr old (83%, n = 58 of 70). Coexisting conditions were typical of this patient population and included Down syndrome (n = 7), former premature infant (n = 4), VACTERL (vertebral anomalies, anal atresia, cardiac defect, tracheoesophageal fistula, renal and limb abnormalities) association, cat eye syndrome, Williams' syndrome, neonatal lupus with heart block, congenital hyperinsulinism, non-

Table 1. Summary of demographic and clinical variables

Variable	Median (Interquartile Range) or % (No.)	
	Acyanotic (n = 46)	Cyanotic (n = 24)
Age, yrs	0.4 (0.1–1.2)	0.03 (0.01–0.4)
Weight, kg	5.5 (3.6–7.5)	3.7 (3.1–5.2)
Male gender, %	59 (27)	46 (11)
Sao ₂ , %	100 (98–100); 507 ^a	82 (79–87); 300 ^a
ScvO ₂ , %	66 (55–77); 146 ^a	52 (41–67); 71 ^a
rSo ₂ forehead, %	64 (56–73); 482 ^a	52 (45–61); 303 ^a
rSo ₂ flank, %	83 (77–91); 179 ^a	66 (53–75); 165 ^a
Paco ₂ , torr	41 (37–45); 407 ^a	44 (38–50); 286 ^a
MAP, mm Hg	60 (52–70); 506 ^a	52 (43–63); 318 ^a
Heart rate, beats/min	145 (132–159); 506 ^a	150 (139–167); 319 ^a
Temperature, °C	36.8 (36.4–37.3); 471 ^a	36.5 (36.1–37.1); 282 ^a
Lactate, mMol/DI	2.1 (1.4–3.2); 280 ^a	2.7 (1.7–4.7); 191 ^a
Hematocrit, %	39.7 (35.2–47); 167 ^a	42.9 (37.9–46.9); 120 ^a

Sao₂, arterial oxygen saturation; ScvO₂, central venous oxygen saturation; rSo₂, regional oxygen saturation; MAP, mean arterial pressure.

^aMeasurement pairs.

Table 2. Summary of congenital heart disease diagnosis by anatomical group

Lesion Classification	Diagnosis	No.	Total No.
Two-ventricle			45
	Atrioventricular septal defect	10	
	TGA	8	
	Tetralogy of Fallot	8	
	VSD	5	
	Atrial septal defect	3	
	Pulmonary atresia, VSD	3	
	Truncus arteriosus	2	
	Totally anomalous pulmonary venous drainage	2	
	Pulmonic stenosis	1	
	Patent ductus arteriosus	1	
	Absent pulmonary valve syndrome	1	
	Aortic insufficiency	1	
Two-ventricle, arch obstruction			5
	Aortic coarctation	4	
	Interrupted aortic arch, VSD	1	
Single-ventricle			9
	Tricuspid atresia/pulmonary atresia	5	
	Right atrial isomerism	2	
	Tricuspid atresia	1	
	Ebstein's anomaly	1	
Single-ventricle, arch obstruction			11
	Hypoplastic left heart syndrome	7	
	Unbalanced atrioventricular septal defect	2	
	TGA, hypoplastic right ventricle	2	

TGA, transposition of the great arteries; VSD, ventricular septal defect.

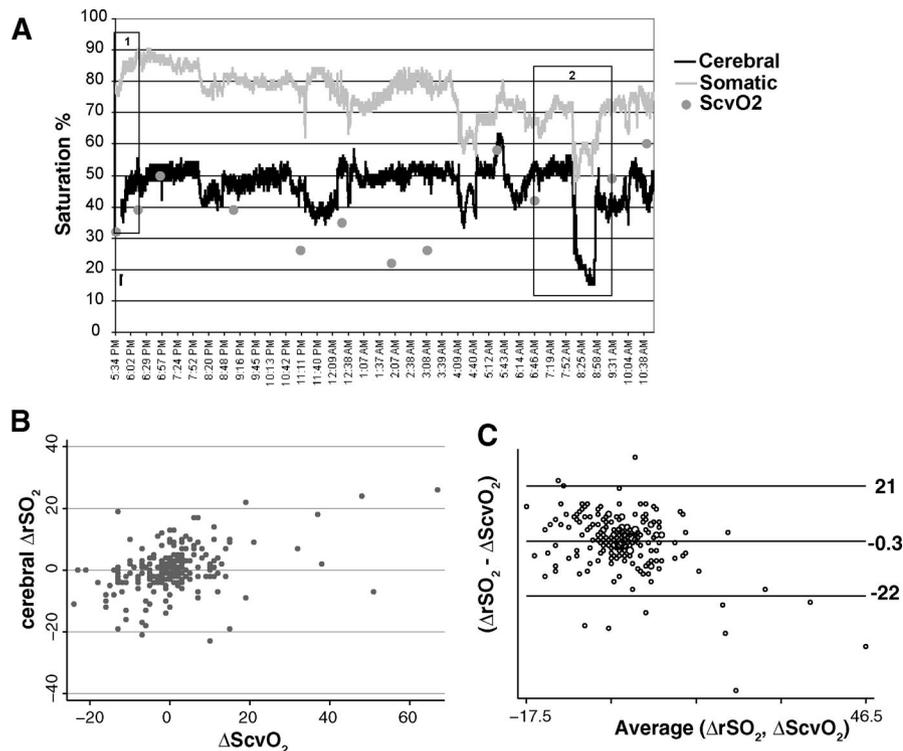


Figure 1. A, example of postoperative regional flank (gray) and cerebral oxygen saturation (%) over time (x axis). Individual central venous oxygen saturation (ScvO₂) values are plotted (gray circles). Two events, representing a pair of ScvO₂ values, are outlined (gray boxes, labeled 1 and 2). Event 1 illustrates an event where ScvO₂ increased in parallel with regional cerebral and flank saturations. Event 2 shows an example where ScvO₂ and flank regional oxygen saturation (rSO₂) increased but cerebral rSO₂ decreased. B, scatter plot of change in ScvO₂ (ΔScvO₂) vs. change in rSO₂ measured by near-infrared spectroscopy (ΔrSO₂). C, Bland-Altman analysis of the difference vs. the mean of cerebral ΔrSO₂ and ΔScvO₂. Mean difference and 95% limits of agreement are noted.

immune hydrops fetalis, and Marfan's syndrome. Complete biventricular repairs were accomplished in more than half of the patients (repair of atrioventricular septal defect, n = 10; repair of atrial septal, ventricular septal defect, n = 8; tetralogy of Fallot repair, n = 8; arterial switch procedure, n = 8; repair of ventricular septal defect and right ventricle to pulmonary artery conduit, n = 3; repair of totally anomalous pulmonary venous connection, n = 2; aortic coarctation repair, n = 1). Palliative procedures were performed in 31% of patients (Norwood procedure, n = 8; modified Blalock-Taussig shunt, n = 7; bidirectional Glenn procedure, n = 5; Fontan procedure, n = 1). Valve repair or replacement was performed in 19% of the study population (n = 12). The patients with postoperative cyanotic physiology (n = 24) were younger (Table 1), consistent with the typical age for palliative procedures that result in residual right to left shunts. Reflective of this age and physiology, cyanotic patients had lower arterial saturation, central venous oxygen saturation, and regional oxygen saturations (Table 1). There were no complications of cerebral oxygen saturation monitoring or data collection.

Recordings were made during the first postoperative day and lasted a median of 21.7 hrs (interquartile range 17.4–22.5). There were no differences in recording duration across lesion categories. Multiple events were identified for each subject (median 7, interquartile range 3–11). The median, interquartile range, and number of all recorded laboratory and physiologic variables are summarized in Table 1.

Regional and Central Venous Saturations Were Correlated But Were Not Substitute Measures. Individual examples of similar (Fig. 1A, box 1) and opposite (Fig. 1A, box 2) changes of the regional and central venous oxygen saturation data can be identified from the raw data plots. Collectively, in the first 24 postoperative hours, ScvO₂ was significantly correlated with cerebral rSO₂ (Spearman's ρ = .7, p < .0001). This association was significant across all cardiac anatomical groups (Spearman's ρ .55–.79, all p < .001) and was similar in those with cyanotic and acyanotic lesions (acyanotic Spearman's ρ = .65, cyanotic Spearman's ρ = .67, both p < .001). Similarly, ScvO₂ was significantly associated with flank rSO₂ (Spearman's ρ = .59, p < .0001).

To determine whether central venous and cerebral oxygen saturations were in-

Table 3. Changes in physiologic and laboratory variables and their relationship to cerebral oximetry

Δ Variable	Cerebral ΔrSo ₂			Flank ΔrSo ₂			ΔScvo ₂		
	Coef.	95% CI	p Value	Coef.	95% CI	p Value	Coef.	95% CI	p Value
ΔPaco ₂	0.3	0.2 to 0.5	<.001	-0.09	-0.2 to 0.05	.2	-0.04	-0.2 to 0.2	.7
ΔSao ₂	0.3	-0.03 to 0.6	.07	0.2	-0.06 to 0.4	.1	0.8	0.2 to 1.3	.01
ΔMAP	0.07	0.02 to 0.1	.008	-0.05	-0.1 to 0.02	.2	0.07	-0.07 to 0.2	.3
ΔHeart rate	-0.3	-0.1 to 0.04	.4	-0.07	-0.2 to 0.02	.1	-0.1	-0.3 to 0.06	.2
ΔTemperature	-0.2	-1.3 to 1.0	.8	-0.9	-2.4 to 0.5	.2	-0.3	-2.3 to 1.6	.7
ΔLactate	-0.5	-1.9 to 0.8	.5	-0.02	-0.7 to 0.6	.9	1.5	-0.04 to 3.1	.06
ΔHematocrit	0.3	-0.02 to 0.6	.07	0.05	-0.3 to 0.4	.7	-0.3	-0.9 to 0.2	.2

rSo₂, regional oxygen saturation; Scvo₂, central venous oxygen saturation; Coef., coefficient; CI, confidence interval; Δ, change; Sao₂, arterial oxygen saturation; MAP, mean arterial pressure. Significant values are indicated by bold typeface.

terchangeable, a Bland-Altman analysis was performed. Cerebral rSo₂ and Scvo₂ had only a -1.0% mean difference (95% confidence interval [CI] -2.7 to 0.6), yet the limits of agreement were large (-25.6 to 23.5%). In contrast, the mean difference between flank rSo₂ and Scvo₂ was 18.4% (CI 15.2-21.7%), indicating that flank rSo₂ tended to be higher than Scvo₂. Again the limits of agreement were wide (-12.5 to 49.4%).

Two-Site NIRS Recording-Relative Cerebral Desaturation. Because of the bias associated with flank but not cerebral rSo₂ and Scvo₂, we investigated the relationship of cerebral and flank rSo₂ over time. Cerebral oxygen saturation lower than flank oxygen saturation was noted initially in the majority of patients (81%, n = 22) monitored with two NIRS sensors. The median difference was -20% (cerebral-flank rSo₂) with a range from -34% to -6%. This pattern persisted for a median of 19 recorded hours (range 2-31 hrs). However, we are underestimating the duration, for in many patients the pattern of cerebral oxygen saturation lower than flank persisted to the end of recording. Relative cerebral desaturation was noted in all patients following regional cerebral perfusion (n = 6) and in 78% of patients following conventional cardiopulmonary bypass (n = 14). Bypass method, age, and gender were not associated with differences in the frequency (all p > .1), magnitude, or duration of relative cerebral desaturation (all p > .1).

Trends in rSo₂ Were No More Accurate Than Isolated Values in Predicting in Scvo₂. To determine whether trends in the change of rSo₂ (ΔrSo₂) and Scvo₂ (ΔScvo₂) were more closely associated than the isolated values, we identified all repeated measures of rSo₂ and Scvo₂ in individual patients and compared the

changes between measurements. Cerebral ΔrSo₂ and ΔScvo₂ were significantly, but less strongly correlated than isolated values (Spearman's ρ .37, p < .0001, Fig. 1B). Similarly, flank ΔrSo₂ and ΔScvo₂ were significantly correlated (.47, p < .0001). Again, Bland-Altman analysis (Fig. 1C) demonstrated wide limits of agreement (cerebral ΔrSo₂ - ΔScvo₂ = -18% to 19%) with a mean difference of -0.3% (CI -1.8 to 1.1), indicating that changes in cerebral oxygen saturation were no more interchangeable with changes in central venous saturation than were the isolated values. Similar results were obtained if patients older than 1 yr were excluded. Bland-Altman analysis of flank ΔrSo₂ and ΔScvo₂ yielded a similar relationship, with a small mean difference (-1.0%, CI -2.9 to 0.9%) and wide limits of agreement (-19.3 to 17.2%).

Concordance of Cerebral Regional and Central Venous or Flank Regional Oxygen Saturation. Although neither isolated values nor change in rSo₂ was interchangeable with Scvo₂, we noted many instances where the variables changed in the same direction (Fig. 1A gray box, event 1). To quantify the frequency that rSo₂ and Scvo₂ changed in parallel direction, we identified events with a change of ≥5% in Scvo₂ (n = 104) or flank rSo₂ (n = 112) and noted the direction of change in cerebral rSo₂. Cerebral rSo₂ changed in the same direction as Scvo₂ in 67 cases (64%, CI 55-73%) and in the same direction as flank rSo₂ in 66 cases (59%, 50-68%). To test the relationship between flank rSo₂ and Scvo₂, we identified events with a change of ≥5% in Scvo₂ (n = 45) and noted the direction of change in flank rSo₂. Flank rSo₂ changed in the same direction as Scvo₂ in 32 cases (71%, CI 57-82%).

Change in Paco₂ Was Associated With Change in Cerebral But Not Flank or Central Venous Saturation. To further understand the physiologic relationships driving change in central venous or regional oxygen saturation, we determined the hematologic, biochemical, and physiologic variables most associated with changes in central and regional oxygen saturation. A significant association was determined for change in Paco₂ (ΔPaco₂, p < .0001) and change in MAP (ΔMAP, p = .008) with cerebral ΔrSo₂ but not flank ΔrSo₂ or ΔScvo₂ (Table 3, Fig. 2, A-F). This association remained significant across all cardiac anatomical groups (all p ≤ .05) and cyanotic or acyanotic physiology (all p < .005). Change in Sao₂ (ΔSao₂) was associated with ΔScvo₂ (p = .01) and trended toward an association with cerebral ΔrSo₂, but this did not reach significance (p = .07) on univariate analysis (Table 3, Fig. 2, G-I). Although ΔSao₂ was associated with the largest magnitude of ΔScvo₂ (β = .75), this association is only significant in cyanotic patients (p = .015) and not in acyanotic patients (p = .5). ΔPaco₂ was associated with the largest cerebral ΔrSo₂ (β = .35). Trends toward association were noted for change in hematocrit with cerebral ΔrSo₂ and change in lactate with ΔSao₂, but these did not reach significance (Table 3). To examine interaction between variables, all four variables that trended toward association (p ≤ .1) with cerebral ΔrSo₂ were tested in a multivariate model. ΔPaco₂ remained significantly associated (p < .001, CI 0.4-0.7) and ΔSao₂ became significantly associated with cerebral ΔrSo₂ (p = .007, CI 0.1-0.9); ΔMAP and Δ hematocrit were not significantly associated with cerebral ΔrSo₂ in this model. Applying the same model to patients younger than 1 yr yielded the same result. Excluding pa-

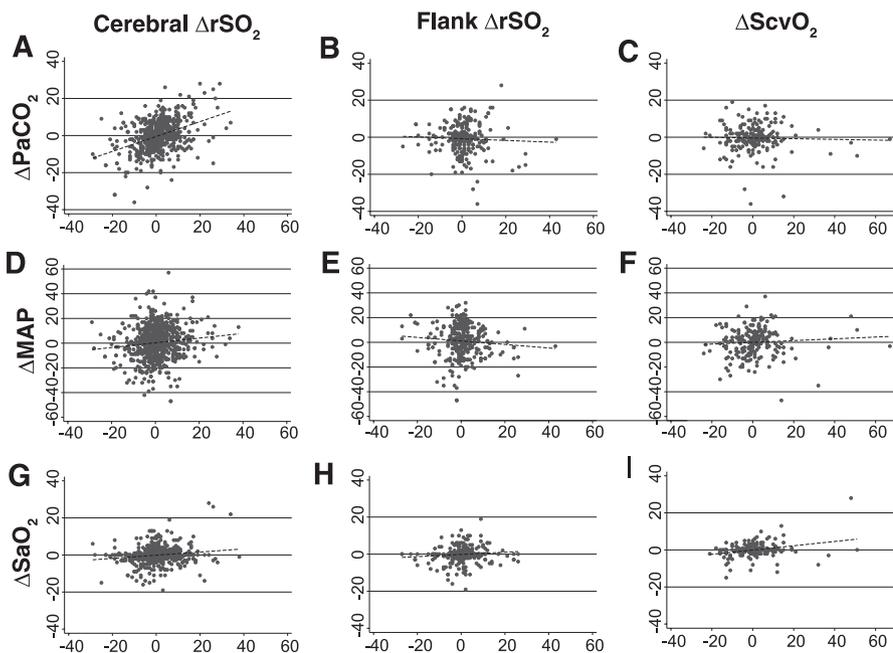


Figure 2. Scatter plots of individual data points for change in cerebral regional oxygen saturation (*cerebral* ΔrSO_2) (A, D, G), flank regional oxygen saturation (*flank* ΔrSO_2) (B, E, H), or central venous oxygen saturation ($\Delta ScvO_2$) (C, F, I) vs. change in $Paco_2$ ($\Delta Paco_2$) (A, B, C), mean arterial pressure (ΔMAP) (D, E, F), or systemic arterial oxygen saturation (ΔSaO_2) (G, H, I). Regression lines (*dashed lines*) are shown for each relationship.

tients with the possibility of left to right atrial shunting also did not alter the selective association of cerebral ΔrSO_2 with $\Delta Paco_2$, nor did this alter the wide limits of agreement between cerebral ΔrSO_2 and $\Delta ScvO_2$ (-20.0 – 18.3).

DISCUSSION

The present study builds on previous studies showing that cerebral rSO_2 and $ScvO_2$ are significantly correlated (6, 13, 14) but have wide limits of agreement (7). The findings that both isolated cerebral and flank rSO_2 were correlated with $ScvO_2$ and that this relationship was true for both cyanotic and acyanotic lesions, as well as across cardiac lesion categories, is important for the clinical application of this technique. However, isolated cerebral rSO_2 and $ScvO_2$ values have very wide limits of agreement (-25.6% to 23.5%), similar to those found in a prior study (7). These authors suggested that cerebral oximetry appeared to be most useful for indicating trends in $ScvO_2$ rather than absolute numbers. To test this hypothesis, we analyzed the change in rSO_2 and $ScvO_2$ and found that both cerebral and flank ΔrSO_2 were significantly correlated with $\Delta ScvO_2$ but had wide limits of agreement. We found that a majority of the time, cerebral rSO_2 changed in the same

direction as $ScvO_2$ (64%) and flank rSO_2 (59%). The concordance between flank rSO_2 and $ScvO_2$ may have been slightly better (71%) but was still far from perfect. A recently published study that included comprehensive measurements of oxygen delivery and consumption in comparison with cerebral and flank regional oximetry in 11 neonates following the Norwood procedure concluded that inter- and inpatient variability limited the clinical interpretation of regional oxygen saturation data to monitor systemic oxygen transport (15).

We found that flank rSO_2 tended to be higher than either cerebral rSO_2 or $ScvO_2$ in the early postoperative period. This pattern of cerebral lower than flank rSO_2 has been reported in single-ventricle patients following regional cerebral perfusion for the Norwood procedure (16). In the present study we found this pattern to be common, even after conventional cardiopulmonary bypass. In particular, this pattern was present in 81% of patients monitored with two-site rSO_2 monitoring, including all patients receiving regional cerebral perfusion, and surprisingly in 78% of patients following conventional cardiopulmonary bypass. Consistent with the high prevalence of this pattern, we noted that, on average, $ScvO_2$ was substantially lower than flank

rSO_2 . As this difference gradually disappeared (median duration 19 hrs) over the first postoperative day, one must be cautious in generalizing the results of the present study beyond the first postoperative day.

To gain insight into the physiology associated with independent changes in rSO_2 and $ScvO_2$, we compared change in clinical variables with change in regional and central venous oxygen saturation. We found that changes in arterial carbon dioxide tension and mean arterial pressure were associated with cerebral ΔrSO_2 but not flank ΔrSO_2 or $\Delta ScvO_2$. Change in arterial oxygen saturation was significantly associated $\Delta ScvO_2$ on univariate analysis and with cerebral ΔrSO_2 in a multivariate model. Given the major contribution of SaO_2 to oxygen delivery, a relationship between ΔSaO_2 and venous oximetry is not unexpected (8) and has been observed specifically for isolated values of cerebral NIRS (14, 15). A positive association between carbon dioxide level and cerebral oxygen saturation has been noted in infants with hypoplastic left heart syndrome managed preoperatively with hypercarbia (5, 17), although this effect was attributed to either increased cerebral blood flow, increased cardiac output, or both. Following superior cavopulmonary anastomosis, hypercarbia significantly increased cerebral oxygen saturation (18). In these patients, higher cerebral oxygen saturation resulted from not only increased cerebral blood flow directly but also increased pulmonary blood flow, increased cardiac output, and decreased systemic vascular resistance and oxygen consumption, leading to improved overall oxygen transport (19). The association between cerebral ΔrSO_2 and $\Delta Paco_2$ in the present study was significant for all cardiac lesion categories, not exclusively in those with single-ventricle physiology. The lack of association of $\Delta ScvO_2$ with $\Delta Paco_2$ suggested that the dominant effect of $\Delta Paco_2$ was on cerebral blood flow, but we cannot rule out an effect on both cerebral blood flow and cardiac output. Clearly, complex cardiopulmonary physiology involves multiple interactions between physiologic variables.

A relationship between ΔMAP and cerebral ΔrSO_2 was observed on univariate analysis, but this did not remain significant in a multivariate model. The observation that cerebral ΔrSO_2 was positively associated with ΔMAP implies an absence of cerebral pressure autoregulation. Evi-

dence for disturbed cerebral pressure autoregulation was noted in 13% of infants following cardiac surgery using NIRS (20). Cerebral pressure autoregulation exists across a range of mean arterial pressures, and the lower limit (~60 mm Hg) has been found not to vary by age (21). Many of the blood pressures recorded in this study were below this limit, especially in the neonates. Thus, for both reasons patients in this study may represent a mixture of disturbed and intact cerebral pressure autoregulation and this may account for why the association between Δ MAP and cerebral Δ rSO₂ was weaker than that for Δ Paco₂.

One explanation for wide limits of agreement between rSO₂ and ScvO₂ may relate to the heterogeneity of sampling sites for ScvO₂. The majority of samples were obtained from the right atrium through surgically placed transthoracic catheters. However, samples were also obtained from the vena cava. Variability in hemoglobin saturation of samples from the right atrium reflects the contributions of superior and inferior vena cava and coronary sinus blood before mixing in the right ventricle. These values differ from each other and from a true mixed venous hemoglobin saturation (22). However, trends in the change of central venous saturation in the right atrium have been found to predict trends in the change of mixed venous saturation (23). Given the noninterventional design of this study, our data reflect current clinical practice in a PCICU. Therefore, we chose to include all ScvO₂ values, regardless of sampling site. For similar reasons, we chose to include three adult patients cared for in our PCICU during the study. However, the major observations in this study remained significant when the analyses were repeated for patients <1 yr of age.

The present data suggest that regional oxygen saturation measured by NIRS cannot precisely predict central venous saturation and therefore should not be considered a substitute. However, changes in central venous and regional oxygen saturation occur in parallel the majority of the time. The unique association of change in Paco₂ with cerebral Δ rSO₂, but not flank Δ rSO₂ or Δ ScvO₂, suggests that cerebral oxygen saturation measured by NIRS may yield unique information about regional cerebral oxygen delivery. If this is indeed the case, one would expect that low values of cerebral rSO₂ would be a risk factor for acquired

brain injury. This association was recently reported in patients with hypoplastic left heart syndrome following the Norwood procedure (24). As improvements in surgical technique have made survival for most forms of congenital heart disease excellent, attention is turning toward improving neurodevelopmental outcome (25). Understanding the pathophysiology of cerebral injury unique to this population, such as relative cerebral desaturation in the postoperative period, will indicate specific interventions. Optimizing cerebral oxygen delivery and preventing postoperative cerebral ischemia can only be achieved with appropriate monitoring, and despite significant technical limitations, cerebral NIRS offers a noninvasive, portable, safe solution for research. The clinical benefit to patient outcomes of cerebral NIRS monitoring needs to be established in prospective trials.

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