Inferior Vena Cava Oxygen Saturation Monitoring After the Norwood Procedure

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Background. **Superior vena cava oxygen saturation monitoring in the early postoperative period after the Norwood procedure (NP) has been associated with improved survival and decreased adverse events (AE). There is no data describing inferior vena cava saturation (S_{IVO_2}) monitoring after NP. We sought to investigate the utility of intermittent S_{IVO_2} monitoring after NP and to assess the correlation of S_{IVO_2} with renal near-infrared spectroscopy (rNIRS). We hypothesized failure to achieve S_{IVO_2} greater than 45% within the first 4 hours after NP is predictive of AE, and that rNIRS correlates with S_{IVO_2}.**

Methods. **A retrospective study of 26 consecutive NP patients who received postoperative management with S_{IVO_2} monitoring according to a strict protocol was conducted. Primary outcome was AE, defined as cardiopulmonary resuscitation, extracorporeal membrane oxygenation, death before discharge, or residual surgical defects.**

Results. **Ten (38%) patients had one or more AE; mortality was 23%. On admission to the cardiac intensive care unit, patients with AE had lower S_{IVO_2} (45% ± 9.4% versus 62% ± 12.0%; $p < 0.001$) and lower rNIRS (56 ± 6.5 versus 77 ± 7.2; $p < 0.001$). At 4 hours, 90% of AE patients had an S_{IVO_2} less than 45% versus 6% of non-AE patients. Both S_{IVO_2} and rNIRS were highly predictive of AE: the area under the receiver-operating characteristic curve was greater than 0.86 and 0.95, respectively. Two hours after admission, an S_{IVO_2} less than 45% predicted AE with a specificity of 93%, a sensitivity of 70%, and a positive predictive value of 82%. The S_{IVO_2} was strongly correlated with rNIRS ($r = 0.81$).**

Conclusions. **Intermittent S_{IVO_2} can be used to guide early postoperative NP management; rNIRS is an accurate continuous, noninvasive surrogate for S_{IVO_2}. An S_{IVO_2} of less than 45% in the first 4 hours after the NP is predictive of AE.**

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The high-risk postoperative period after the Norwood procedure with right ventricle to pulmonary artery conduit (NP) has been well documented. The deleterious effects of cardiopulmonary bypass (CPB), ventriculotomy, and ischemia–reperfusion lead to dysfunction of the single right ventricle that is responsible for supplying cardiac output (CO) simultaneously to both the pulmonary ($\dot{Q}p$) and systemic ($\dot{Q}s$) circulations. There is minimal total CO reserve, so even small changes in oxygen delivery or consumption can lead to anaerobic metabolism, lactic acidosis, and eventual cardiovascular collapse. This volatile physiology is exacerbated by the labile vascular resistances inherent in the neonatal period with resultant imbalances in $\dot{Q}p/\dot{Q}s$. A management goal for NP patients encompasses early identification of compromised oxygen delivery such that interventions can be made before clinical deterioration. Superior vena cava oxygen saturation (S_{SVO_2}) monitoring is commonly used as an estimate of systemic oxygen delivery in the early postoperative period, and identifies shock before changes in traditional surrogates of CO, such as blood pressure, arterial oxygen saturations, and serum lactate [1, 2]. Inability to optimize S_{SVO_2} in the early postoperative period is associated with increased risk of morbidity and mortality [3–5]. Recently, the use of near-infrared spectroscopy (NIRS) to provide a continuous, noninvasive estimate of S_{SVO_2} has gained prominence and identifies patients at risk for adverse events (AE) [6, 7].

The utility of monitoring inferior vena cava saturation (S_{IVO_2}) after complex neonatal cardiac surgery has not been described. A fall in S_{IVO_2} may be an earlier indicator of limited CO and decreased oxygen delivery when compared with S_{SVO_2}. In patients with normal physiology, there is redistribution of blood flow away from splanchnic and renal beds during early shock, while perfusion to the cerebral and coronary circulations is preserved [8]. This leads to increased oxygen extraction in the abdominal organs, which decreases S_{IVO_2} but not S_{SVO_2}, as blood flow to the brain will be maintained until later stages of shock.

The goal of this study was to determine whether S_{IVO_2} monitoring or renal NIRS (rNIRS) could identify those

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Abbreviations and Acronyms

AE	= adverse event
AUC	= area under the curve
CICU	= cardiac intensive care unit
cNIRS	= cerebral near-infrared spectroscopy
CO	= cardiac output
CPB	= cardiopulmonary bypass
CPR	= cardiopulmonary resuscitation
CVL	= central venous line
ECMO	= extracorporeal membrane oxygenation
NIRS	= near-infrared spectroscopy
NP	= Norwood procedure
POD	= postoperative day
$\dot{Q}p$	= pulmonary circulation
$\dot{Q}s$	= systemic circulation
rNIRS	= renal near-infrared spectroscopy
S_{IVO_2}	= inferior vena cava oxygen saturation
S_{SVO_2}	= superior vena cava oxygen saturation

patients at highest risk for AE in the early postoperative period. Hypotheses to be tested were (1) an inability to achieve target S_{IVO_2} of greater than 45% in the first 4 hours after cardiac intensive care unit (CICU) admission is associated with increased incidence of AE; (2) rNIRS monitoring in the first 4 hours can discriminate patients at risk for AE; and (3) rNIRS and S_{IVO_2} are correlated, enabling rNIRS to be used as an effective continuous, noninvasive surrogate for oxygen transport balance.

Patients and Methods

Patient Selection and Data Collection

The study was approved by the Institutional Review Board of the University of Alabama at Birmingham. This is a retrospective study of 26 consecutive patients who underwent NP from March 2010 to November 2011. We use only femoral central venous lines (CVL) in all single-ventricle patients to avoid the consequences of upper central vein thrombosis. Patients were eligible for inclusion into this study if they had a femoral CVL and were managed according to the postoperative NP protocol. Patients were excluded if they were placed on extracorporeal membrane oxygenation (ECMO) in the operating room. Hemodynamic and oximetry data at CICU admission and at 2 and 4 hours (Table 1) was extracted from bedside flow sheets that were prospectively completed by nurses as part of the NP protocol. All other data, including AE, were collected from our CICU clinical database. Adverse event was defined a priori as death before discharge, cardiopulmonary resuscitation, emergent ECMO, or residual surgical defects.

Operative Procedure

After median sternotomy, CPB was established with arterial cannulas in the base of the innominate artery and in the ductus arteriosus along with bicaval venous cannulation. All patients received a single dose of del Nido

Table 1. Comparison of Hemodynamic and Oxygen Transport Variables[a]

Variable	Adverse Events (n = 10)	No Adverse Events (n = 16)	*p* Value
Femoral venous oxygen saturation (%)			
Admission	45 ± 9.5	62 ± 12.0	<0.001
2 hours after admission	37 ± 11.9	59 ± 9.4	<0.001
4 hours after admission	34 ± 9.5	60 ± 7.5	<0.001
Renal NIRS (%)			
Admission	56 ± 6.5	77 ± 7.2	<0.001
2 hours after admission	56 ± 7.8	74 ± 7.5	<0.001
4 hours after admission	54 ± 9.9	76 ± 5.8	0.001
Cerebral NIRS (%)			
Admission	44 ± 8.0	45 ± 8.4	0.805
2 hours after admission	41 ± 6.0	46 ± 8.8	0.072
4 hours after admission	42 ± 6.0	48 ± 8.8	0.036
Arterial oxygen saturation (%)			
Admission	70 ± 10.2	75 ± 9.5	0.227
2 hours after admission	71 ± 9.0	77 ± 8.2	0.111
4 hours after admission	68 ± 10.1	76 ± 5.5	0.025
Pulse oximetry (%)			
Admission	82 ± 5.9	80 ± 6.3	0.518
2 hours after admission	80 ± 5.0	80 ± 4.8	0.995
4 hours after admission	80 ± 7.4	79 ± 4.4	0.906
Mean arterial pressure (mm Hg)			
Admission	52 ± 8.7	52 ± 7.6	0.988
2 hours after admission	51 ± 4.5	56 ± 5.5	0.028
4 hours after admission	46 ± 6.7	57 ± 7.1	0.001
Pulse pressure (mm Hg)			
Admission	15 ± 3.2	25 ± 4.6	<0.001
2 hours after admission	17 ± 3.8	30 ± 7.5	<0.001
4 hours after admission	17 ± 4.7	29 ± 5.9	<0.001
Inotropic agent score			
Admission	21.4 ± 11.2	16.3 ± 5.0	0.203
2 hours after admission	24.3 ± 16.2	16.2 ± 5.7	0.156
4 hours after admission	25.0 ± 11.6	15.7 ± 4.4	0.034
Lactic acid (mmol/L)			
Admission	15.3 ± 5.3	8.4 ± 2.7	0.002
2 hours after admission	14.1 ± 4.0	7.8 ± 3.0	0.001
4 hours after admission	13.2 ± 5.7	7.1 ± 3.1	0.009
pH			
Admission	7.32 ± 0.6	7.39 ± 0.1	0.02
2 hours after admission	7.34 ± 0.7	7.40 ± 0.1	0.052
4 hours after admission	7.36 ± 0.1	7.42 ± 0.1	0.073

[a] All numbers are presented as mean ± standard deviation.

NIRS = near-infrared spectroscopy.

cardioplegia solution and were cooled to 22°C. Continuous low-flow cerebral perfusion was used for all cases during arch reconstruction. The aortic arch reconstruction was completed using a patch of bovine pericardium for augmentation after coarctectomy. A 5-mm or 6-mm (based on weight) ringed Gore-Tex (W,L, Gore & Assoc, Flagstaff, AZ) shunt was placed from the right ventricle to the pulmonary artery bifurcation, with patch