Multisite Near-Infrared Spectroscopy Predicts Elevated Blood Lactate Level in Children After Cardiac Surgery

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Objectives: To determine if a relationship exists between regional oxyhemoglobin saturation (rSO_2) measured at various body locations by near-infrared spectroscopy (NIRS) and blood lactate level in children after cardiac surgery.

Design: A prospective, observational study.

Setting: A pediatric cardiac intensive care unit in a university hospital.

Participants: Twenty-three children undergoing repair of congenital heart disease. Patients with single-ventricle physiology and/or residual intracardiac shunts were excluded.

Interventions: None.

Measurements and Main Results: Cerebral, splanchnic, renal, and muscle rSO_2 values were recorded every 30 seconds via NIRS for 24 hours postoperatively. Blood lactate levels measured minimally at 0, 2, 4, 6 and 24 hours postoperatively were correlated with rSO_2 values derived by averaging all values recorded during the 60 minutes preceding the blood draw. Twenty-three patients were enrolled with 163 lactate measurements and more than 39,000 rSO_2 observations analyzed. Cerebral rSO_2 had the strongest inverse correlation with lactate level followed by splanchnic, renal, and muscle rSO_2 ($r = -0.74$, $p < 0.0001$, $r = -0.61$, $p < 0.0001$, $r = -0.57$, $p < 0.0001$, and $r = -0.48$, $p < 0.0001$, respectively). The correlation improved by averaging the cerebral and renal rSO_2 values ($r = -0.82$, $p < 0.0001$). Furthermore, an averaged cerebral and renal rSO_2 value $\leq$65% predicted a lactate level $\geq$3.0 mmol/L with a sensitivity of 95% and a specificity of 83% ($p = 0.0001$).

Conclusions: Averaged cerebral and renal rSO_2 less than 65% as measured by NIRS predicts hyperlactatemia (>3 mmol/L) in acyanotic children after congenital heart surgery. Hence, this noninvasive, continuous monitoring tool may facilitate the identification of global hypoperfusion caused by low cardiac output syndrome in this population.

KEY WORDS: congenital heart disease, near-infrared spectroscopy, cerebral oximetry, congenital heart surgery

THE ACCURATE ASSESSMENT OF global tissue perfusion is crucial in the management of children after cardiac surgery. Multiple clinical and biochemical modalities are commonly used to gauge the adequacy of tissue oxygen delivery during this critical period. These include monitoring of vital signs, physical examination, and laboratory data. Each of these parameters has limitations in that it may be subjective, contingent on the experience of the examiner, invasive, intermittently monitored, or a late finding of poor perfusion.

Blood lactate level is a biochemical marker frequently used to assess global tissue perfusion. Hyperlactatemia often represents anaerobic metabolism, which occurs with inadequate oxygen delivery or impaired oxygen utilization.[1-4] Furthermore, an elevated lactate level is associated with an increased risk for morbidity and mortality after pediatric cardiac surgery.[5-8] However, the measurement of blood lactate level is limited in that it is invasive and intermittent, and, consequently, an acute deterioration may be missed. In addition, frequent blood sampling leads to increased blood loss and an increased risk of infection.[9,10]

Near-infrared spectroscopy (NIRS) has been used to measure regional tissue oxyhemoglobin saturation (rSO_2).[11,12] Previous studies have provided some evidence that low rSO_2 values reflect impaired global tissue perfusion by comparison with mixed venous saturation and the development of organ dysfunction.[9,13-18] To date, the relationship between blood lactate level and rSO_2 in patients with congenital heart disease has not been described. Therefore, the authors sought to determine if a correlation exists between rSO_2 measured at various sites and blood lactate level as a marker of impaired tissue oxygen delivery in children after cardiac surgery.

MATERIALS AND METHODS

The authors conducted a prospective, institutional review board–approved study. All patients who underwent congenital heart surgery requiring cardiopulmonary bypass at the authors' institution between April and December 2006 were eligible. Patients with single-ventricle physiology and those with residual intracardiac shunts on postoperative transesophageal echocardiography were excluded in order to eliminate arterial desaturation as a possible confounding factor contributing to the variability in NIRS values. Informed consent was obtained from each patient's parent or legal guardian before enrollment.

Cerebral rSO_2 is routinely monitored intraoperatively by using a NIRS device (INVOS 5100; Somanetics Corp, Troy, MI) in patients undergoing congenital heart surgery at the authors' institution. These devices rely on the fact that the absorbance spectrum of hemoglobin depends on its oxygenation status. The INVOS 5100 has a light source that delivers near-infrared light at 2 wavelengths (730 and 805 nm) of known intensity to tissues and 2 detectors that measure the intensity of the reflected light. The change in the intensity is dependent on the oxyhemoglobin-to-deoxyhemoglobin ratio; therefore, an oxyhemoglobin saturation can be derived.[19,20] Unlike pulse oximetry, which focuses on pulsatile flow, NIRS technology incorporates the total light signal. Because the greatest contribution to a tissue's absorption spectrum is from blood contained within capillaries, venules, and veins, rSO_2 is a venous-weighted value.[21]

In each patient, self-adhesive Somasenors (Somanetics Corp) were placed in 4 locations, designated as cerebral (right forehead), splanchnic (2 cm below umbilicus), renal (right flank), and skeletal muscle (right rectus femoris) sites, upon admission to the pediatric cardiac intensive care unit. Regional oxyhemoglobin saturation values for each of the specified locations were recorded every 30 seconds for 24 hours postoperatively. Blood lactate levels, obtained from a peripheral arte-

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Table 1. Patient Demographics and Clinical Variables

Variable	Median	Mean Deviation	Range
Age (y)	0.5	1.4	1-12
Weight (kg)	5.3	5.1	2.9-49.0
RACHS Score*	3	0.7	2-4
Heart rate (beats/min)	136	16.1	78-186
Mean arterial pressure (mmHg)	59	10.4	35-92
Temperature (°C)	36.8	0.6	33.1-39.0
Lactate (mmol/L)	1.3	1.2	0.5-9.0
Arterial pH	7.4	0.1	7.1-7.6
PCO_2 (mmHg)	44	7.2	29-90
PO_2 (mmHg)	96	44.8	24-500
Oxygen saturation (%)	98	5.1	44-100
Hematocrit (%)	36	4.6	21-52
Cardiopulmonary bypass time (min)	129	41	66-218

*RACHS Score, Risk Adjustment for Congenital Heart Surgery Score.[23]

rial catheter, were measured minimally at 0, 2, 4, 6, and 24 hours after admission to the pediatric cardiac intensive care unit. Occasionally, additional lactate measurements were obtained if clinically indicated. The NIRS devices used in this study allowed 2 channels to be measured and recorded simultaneously. Therefore, 2 devices were used on each patient in order to monitor the 4 sites continuously. Additional data, including sex, age, weight, Risk Adjustment for Congenital Heart Surgery (RACHS) score, presence of a noncardiac anomaly, heart rate, mean arterial pressure, temperature, pH, pCO_2, pO_2, pulse oximetry, hematocrit, and cardiopulmonary bypass time were collected from the patient record.[22]

Statistical analyses were performed by using Minitab Software (Minitab, Inc, State College, PA). For each of the 4 designated sites, rSO_2 values corresponding to each blood lactate level were derived by averaging all values recorded during the 60 minutes preceding the blood draw. Pearson correlation coefficients were calculated in order to examine the relationships among lactate, rSO_2, and the other clinical variables. Subsequently, a stepwise, multiple regression analysis was performed by using only those variables found to be significantly associated with lactate in order to determine which factors were the strongest predictors of blood lactate level. Additionally, receiver operating characteristic curve analysis was used in order to determine the optimal combination of sites and the threshold rSO_2 value for the prediction of hyperlactatemia.

Table 2. Diagnoses and Distribution of Patients

Diagnosis	No. of Patients
Ventricular septal defect	1
Ventricular septal defect, double-chamber right ventricle	2
Tetralogy of Fallot	3
Ventricular septal defect, coarctation of the aorta	1
Atrial septal defect, ventricular septal defect, coarctation of the aorta	2
Complete atrioventricular canal	2
Congenital mitral regurgitation	1
Supravalvar aortic stenosis	2
Tetralogy of Fallot, pulmonary atresia	2
Transposition of the great arteries	2
Tetralogy of Fallot, pulmonary atresia, major aortopulmonary collaterals	3
Ventricular septal defect, interrupted aortic arch	2

RESULTS

Twenty-three patients were enrolled, 13 males and 10 females, with a median age of 0.5 years, a median weight of 5.4 kg, and a median RACHS score of 3. Patient demographics and clinical variables are summarized in Table 1. The diagnoses were varied and are listed in Table 2. In total, 163 lactate measurements were recorded, of which 18% had a value greater than 3 mmol/L. In total, more than 39,000 rSO_2 observations were analyzed.

For each of the designated sites, the derived average rSO_2 values were plotted as a function of the corresponding lactate level (Fig 1A). This revealed that the relationship between rSO_2 and lactate was exponential in nature; therefore, a logarithmic transformation of all rSO_2 values was performed before further analysis. When data collected at all time points were analyzed collectively, calculation of Pearson correlation coefficients re-

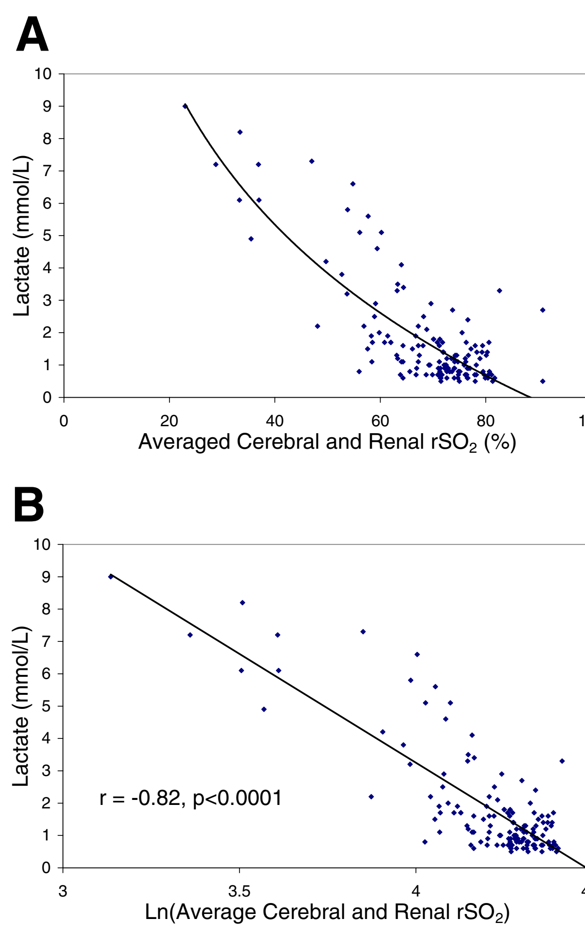

Fig 1. Scatter plots of lactate level as a function of the corresponding rSO_2 values showing the exponential relationship between the 2 variables. (A) Lactate versus averaged cerebral and renal rSO_2. (B) Lactate versus the natural logarithm of averaged cerebral and renal rSO_2 showing their strong inverse correlation. (Color version of figure is available online.)