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Article

Perioperative Changes in Cardiac Index and Regional Tissue Oxygen Saturation in Neonates With Congenital Heart Disease: A Prospective Observational Study

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Abstract

Objective: This study aimed to investigate the trends in cardiac index (CI) and regional tissue oxygen saturation during the perioperative period in neonates undergoing cardiac surgery and evaluate the impact of these changes on postoperative outcomes. **Methods**: This prospective observational study included neonates with congenital heart disease who underwent corrective surgery. The CI was measured at different stages of the perioperative period using electrical velocimetry, while cerebral and somatic oxygen saturation levels were assessed using near-infrared spectroscopy (NIRS). The patients were divided into two groups according to the duration of mechanical ventilation, and the changes in these parameters were explored in the perioperative period between the two groups. **Results**: A total of 32 neonates who underwent corrective cardiac surgery were included, with eight patients categorized in the prolonged mechanical ventilation (PMV) group. Heart function was observed to reach its lowest point within the first 24 hours post-surgery, followed by a gradual recovery. Neonates in the PMV group exhibited lower preoperative CI values (3.0 vs. 3.6; $p < 0.05$), longer postoperative intensive care unit (ICU) length of stay (10.5 vs. 7.0; $p < 0.05$), and lower CI values 48 hours post-surgery (2.26 vs. 2.94; $p < 0.05$). **Conclusions**: This prospective pilot study provides preliminary evidence that delayed recovery of CI and persistent tissue hypoperfusion in the first 48 postoperative hours are associated with PMV in neonates undergoing cardiac surgery.

Keywords

neonates; cardiac surgery; cardiac output; oxygen saturation; perioperative period

Introduction

Neonates undergoing cardiac surgery face unique challenges. Meanwhile, despite the outcomes of cardiac surgery for neonates with congenital heart disease improving recently due to advancements in surgical techniques and treatment strategies, postoperative morbidity and mortality remain high in this vulnerable neonate population [1]. Decreased cardiac function, inadequate tissue perfusion, and insufficient oxygen delivery at the cellular level are frequently associated with poor surgical outcomes [2–4]. The cardiac index (CI), a critical hemodynamic parameter, reflects cardiac output normalized to body surface area and provides valuable insights into cardiovascular status. Additionally, regional tissue oxygen saturation (rSO_2), which reflects post-capillary tissue oxygenation, can serve as an indirect measure of local tissue oxygen utilization [5]. However, the dynamic changes in these parameters throughout the perioperative period in neonates are poorly understood. Thus, investigating these fluctuations is essential for optimizing perioperative management strategies and improving postoperative outcomes.

Most current techniques for measuring cardiac output are invasive; thus, universal application in the neonatal population is challenging. Transthoracic bio-impedance cardiography is an advanced, non-invasive method for measuring cardiac output [6]. The ICON® monitor (Osypka Medical, Berlin, Germany) provides continuous beat-to-beat cardiac output measurements through a patented algorithm that detects changes in chest electrical impedance due to blood flow within the thoracic aorta. The ICON® device has been validated against invasive and other non-invasive cardiac output measurement methods in neonates and infants with congenital heart disease, with no significant bias found based on the type of congenital disability [7–10].

Near-infrared spectroscopy (NIRS) is another non-invasive technique commonly used to monitor cerebral (ScO_2) and somatic (StO_2) oxygen saturation [5]. NIRS provides real-time information on tissue oxygenation and organ perfusion by assessing regional hemoglobin oxygenation, which is critical for perioperative management.

This technique has proven valuable in monitoring neonates with congenital heart disease, who often exhibit complex and unique hemodynamic pathophysiology due to cardiovascular malformations.

Therefore, this study aimed to monitor the perioperative changes in CI, ScO_2, and StO_2 in neonates with congenital heart disease, explore the relationship between these parameters and clinical outcomes, and enhance our understanding of the pathophysiological characteristics during this critical period.

Materials and Methods

This prospective observational study was performed at the Pediatric Cardiac Center, Beijing Anzhen Hospital, Capital Medical University, China, between June 2023 and November 2023. The protocol was approved by the ethics committee at this hospital (No. 2023222X).

Study Population

Neonates diagnosed with congenital heart disease who underwent cardiac surgery (with cardiopulmonary bypass (CPB)) during the study period were considered for inclusion. Surgical interventions included both complete corrective surgery and staged procedures. The exclusion criteria were defined as follows: (1) absence of CPB procedures; (2) presence of major non-cardiac congenital anomalies (e.g., neural tube defects, gastrointestinal atresia); (3) isolated ligation of patent ductus arteriosus (PDA); (4) incomplete clinical datasets (Fig. 1). Due to the exploratory nature of this study and the limited availability of the population, a convenient sample of 32 participants was included.

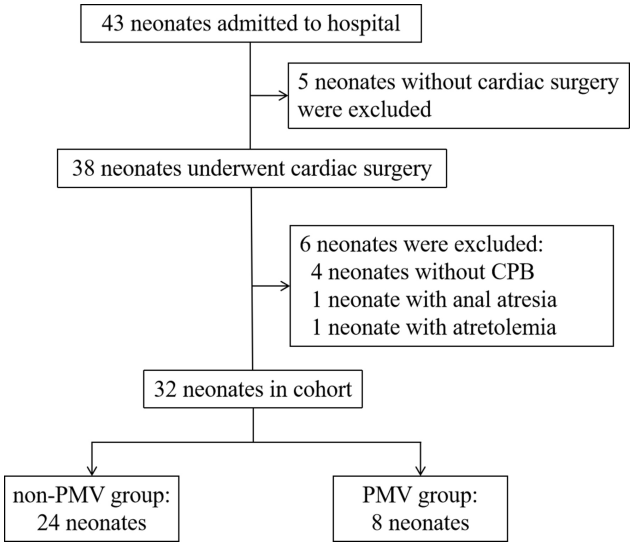

Fig. 1. Flowchart of the study. CPB, cardiopulmonary bypass; PMV, prolonged mechanical ventilation.

Anesthesia and Perfusion Management

The anesthesiology team developed an individualized anesthesia management plan based on the diagnosis and clinical condition of each patient. Sevoflurane was used as the inhaled anesthetic, while sufentanil, ketamine, midazolam, and rocuronium were administered intravenously. Following anesthesia induction, standard monitoring was implemented: central venous pressure measurement through a central venous catheter inserted in the internal jugular vein or femoral vein; systemic arterial blood pressure monitoring via catheterization of the femoral or brachial artery; urine output monitoring with an indwelling urinary catheter; core body temperature measurement using temperature probes placed in the esophagus/nasopharynx or rectum. For neonatal CPB, a specialized tubing set was prepared, pre-filled with approximately 230 mL of pre-flush fluid, and maintained at 35 °C. The pre-flush consisted of a suspension of red blood cells, 20% human albumin, a compound electrolyte solution, 5% sodium bicarbonate, and a heparin sodium solution. CPB was initiated once the activated clotting time (ACT) exceeded 480 seconds, and vacuum-assisted venous drainage was employed to support venous return. After completing CPB, modified ultrafiltration was performed to optimize fluid balance and enhance postoperative recovery.

Cardiac Index Monitoring

Cardiac output was measured non-invasively in enrolled patients using the ICON® monitor (Osypka Medical, Berlin, Germany). The CI was used to facilitate inter-individual comparisons across subjects of varying heights and weights since the CI normalizes cardiac output to body surface area ($L/(min \cdot m^2)$). Four skin sensors were accurately placed on the forehead, left neck, left chest wall, and upper thigh of each patient, according to the manufacturer's specifications. CI measurements were recorded when the monitor screen displayed a green signal, indicating stable readings, and the patient was calm. Baseline CI values were recorded 1 hour before the initiation of anesthesia. Hemodynamic data were collected at the following time points: 0, 8-, 16-, 24-, and 48-hours post-surgery. Monitoring was continued for 15 minutes at each time point, and the average value was calculated as the CI value for that time point.

Regional Oxygen Saturation Monitoring

Regional tissue oxygen saturation was measured using the INVOSTM 5100C (Medtronic, Minnesota, United States). The somatic sensor was placed over the left or right flank at the T12–L2 vertebral level, while the cerebral sensor was positioned on the left or right forehead, between the eyebrow and hairline. Baseline ScO_2 and StO_2 values were recorded before anesthesia. Once the patient entered the operating room, the sensors were attached to monitor changes

in oxygen saturation at these two sites continuously. Key intraoperative time points were documented, including the start of CPB, aortic clamping and unclamping, end of CPB, modified ultrafiltration, and associated clinical data were extracted. After surgery, patients were transferred to the intensive care unit (ICU), where continuous monitoring was continued for 48 hours. The monitoring system recorded all data, which were downloaded to a storage device for statistical analysis.

Data Collection and Definitions

Perioperative data were collected from the clinical electronic medical record system, including general patient characteristics, laboratory test results, intraoperative CPB parameters, and postoperative complications. Arterial blood gas analysis was performed every 4 hours post-surgery, and serum lactate levels were recorded. The vasoactive-inotropic score (VIS) was calculated using the following formula [11]:

VIS = dopamine dose (μg/kg/min) + dobutamine dose (μg/kg/min) + 100 × epinephrine dose (μg/kg/min) + 10 × milrinone dose (μg/kg/min) + 10,000 × vasopressin dose (U/kg/min) + 100 × norepinephrine dose (μg/kg/min).

Based on previous studies [12], prolonged mechanical ventilation (PMV) was defined as a duration of mechanical ventilation greater than or equal to 96 hours. Patients were then divided into two groups: PMV and non-PMV.

Statistical Analysis

The normality of continuous variables was evaluated using the Shapiro–Wilk test. Normally distributed continuous variables were expressed as the mean ± standard deviation (SD) and were compared using the independent two-sample *t*-test. Non-normally distributed continuous variables were presented as the median and interquartile range (IQR) and were compared using the Mann–Whitney U test. Categorical variables are presented as counts and percentages, and comparisons were made using Fisher's exact test. Repeated measures data were analyzed using two-way repeated measures analysis of variance (ANOVA). Statistical analyses were performed using SPSS v. 22.0 (IBM Corporation, Armonk, NY, USA), and statistical graphs were created with GraphPad Prism 7.00 GraphPad Software, Boston, Massachusetts USA, https://www.graphpad.com/). All tests were two-tailed, and a p-value < 0.05 was considered statistically significant.

Results

Patient Characteristics

A total of 32 neonates diagnosed with congenital heart disease were included in the study following the application of the inclusion and exclusion criteria. Among the participants, 21 (65.6%) were male, with a mean age of 12.2 (± 1.0) days. The baseline characteristics of the patients are presented in Table 1. The patients were divided into two groups based on the duration of postoperative mechanical ventilation: the PMV group (≥96 hours) and the non-PMV group (<96 hours). Three neonates were premature, with gestational ages of 36 weeks (n = 2) and 35 weeks (n = 1). The most common cardiac malformation in the cohort was the Tetralogy of Fallot (n = 11, 34.3%), followed by coarctation of the aorta (n = 7, 21.8%). Preoperative regional oxygen saturation levels were similar between the two groups, with no significant difference in cerebral oxygen saturation (ScO_2) (63.4 ± 14.3% vs. 62.9 ± 9.2%; $p = 0.909$). However, the PMV group had significantly lower StO_2 levels than the non-PMV group (50.8 ± 14.1% vs. 67.8 ± 12.5%; $p = 0.011$). Additionally, the CI was lower in the PMV group compared to the non-PMV group (3.0 ± 0.82 vs. 3.6 ± 0.75; $p = 0.044$). No significant difference between the two groups was observed in left ventricular ejection fraction (LVEF) (68.1 ± 5.1% vs. 69.2 ± 4.7%; $p = 0.581$).

Perioperative Outcomes

All patients underwent corrective cardiac surgery, with none requiring palliative surgery. The perioperative data are summarized in Table 2. The non-PMV group had a significantly shorter duration of mechanical ventilation compared to the PMV group [48.3 (46.0–72.0) hours vs. 120.3 (104.9–178.4) hours; $p < 0.001$]. There was no significant difference between the groups regarding the duration of CPB or aortic cross-clamp time. The maximum value of the VIS after surgery was significantly higher in the PMV group compared to the non-PMV group [14.0 (10.3–18.8) vs. 10.0 (8.0–15.0); $p = 0.038$]. The use of vasoactive inotropes was most frequently required for dopamine, followed by dobutamine, epinephrine, milrinone, and norepinephrine. One patient diagnosed with d-transposition of the great arteries underwent an arterial switch operation and was altered from CPB to extracorporeal membrane oxygenation (ECMO) during surgery. The sternum of the patient was not immediately closed, and the patient was transferred to the ICU. The LVEF of this patient was 9% on the first postoperative day and 15% on the second day. Therefore, this extreme value was removed from the statistical analysis of the postoperative LVEF values for patients. Unfortunately, the patient failed to recover from ECMO and died postoperatively. The LVEF values in the remaining patients decreased on the first day after surgery and returned to basal levels on the second; no significant difference in the LVEF values was observed between the two groups.

Table 1. Patient characteristics and preoperative data.

Variables	All patients (n = 32)	PMV (n = 8)	non-PMV (n = 24)	*p*-value
Age at surgery (d), median (IQR)	11.5 (9.0–17.0)	14.5 (6.8–178.3)	11.5 (9.0–15.0)	0.616
Weight (kg), median (IQR)	3.4 (3.0–3.7)	2.9 (2.7–3.3)	3.4 (3.2–3.8)	0.055
Body length (cm), median (IQR)	50 (49.0–52.0)	50 (47.5–50.0)	50 (49.0–51.5)	0.345
Gender (male), n (%)	21 (65.6)	4 (50.0)	17 (70.8)	0.397
Prematurity, <37 weeks, n (%)	3 (9.4)	1 (12.5)	2 (8.3)	1.000
Inotropic agents use, n (%)	7 (21.9)	3 (37.5)	4 (16.5)	0.327
PGE use, n (%)	13 (40.6)	3 (37.5)	10 (41.7)	1.000
Ventilatory support, n (%)	2 (6.3)	1 (12.5)	1 (4.2)	0.444
ScO_2 (%), mean (SD)	63.0 (10.5)	63.4 (14.3)	62.9 (9.2)	0.909
StO_2 (%), mean (SD)	63.5 (14.7)	50.8 (14.1)	67.8 (12.5)	0.011
CI (L/(min × m^2)), mean (SD)	3.4 (0.81)	3.0 (0.82)	3.6 (0.75)	0.044
LVEF (%), mean (SD)	68.9 (4.7)	68.1 (5.1)	69.2 (4.7)	0.581
Cardiac lesion types, n (%)				0.486
Tetralogy of Fallot	11 (34.3)	3 (37.5)	8 (33.3)	-
Ventricular septal defect	5 (15.6)	0 (0)	5 (20.8)	-
Coarctation of aorta	7 (21.8)	2 (25.0)	5 (20.8)	-
Interrupted aortic arch	3 (9.4)	1 (12.5)	2 (8.3)	-
Pulmonary atresia	2 (6.2)	0 (0)	2 (8.3)	-
d-transposition of the great arteries	3 (9.4)	1 (12.5)	2 (8.3)	-
Total anomalous pulmonary venous connection	1 (3.1)	1 (12.5)	0 (0)	-

PMV, prolonged mechanical ventilation; IQR, interquartile range; ScO_2, cerebral oxygen saturation; StO_2, somatic oxygen saturation; CI, cardiac index; PGE, prostaglandin E; LVEF, left ventricular ejection fraction.

Table 2. Intraoperative and postoperative data.

Variables	All patients (n = 32)	PMV (n = 8)	non-PMV (n = 24)	*p*-value
Cardiopulmonary bypass time (min), median (IQR)	144.0 (107.8–210.8)	138.5 (112.5–217.3)	144.0 (106.3–210.8)	0.828
Aortic cross-clamp time (min), median (IQR)	98.5 (65.3–134.0)	95.0 (66.3–138.8)	101.5 (65.3–134.0)	0.931
Underwent DHCA, n (%)	10 (31.3)	3 (37.5)	7 (29.2)	0.681
Minimum nasopharyngeal temperature (°C), mean (SD)	29.5 (1.5)	29.1 (1.3)	29.6 (1.5)	0.917
LVEF on day 1 post-operation (%), mean (SD)	59.0 (8.2)	59.3 (6.2)	58.9 (8.8)	0.919
LVEF on day 2 post-operation (%), mean (SD)	66.2 (5.4)	65.9 (3.8)	66.3 (5.9)	0.841
Duration of invasive mechanical ventilation (h), median (IQR)	70.5 (46.0–97.1)	120.3 (104.9–178.4)	48.3 (46.0–72.0)	0.000
Maximum VIS, median (IQR)	10.0 (8.3–15.8)	14.0 (10.3–18.8)	10.0 (8.0–15.0)	0.038
ICU LOS (d), median (IQR)	7.5 (6.3–9.8)	10.5 (8.0–15.0)	7.0 (5.3–8.0)	0.007
Hospital LOS (d), mean (SD)	13.1 (6.1)	17.3 (9.4)	11.8 (3.8)	0.013
Hospital mortality, n (%)	1 (3.1)	1 (12.5)	0 (0)	0.250
Delayed sternal closure, n (%)	1 (3.1)	1 (12.5)	0 (0)	0.250
Peritoneal dialysis, n (%)	7 (21.9)	4 (50.0)	3 (12.5)	0.047
Complications, n (%)				
Arrhythmia requiring therapy	6 (18.8)	2 (25.0)	4 (16.7)	0.625
Chylothorax	1 (3.1)	0 (0)	1 (4.2)	1.000
Wound infection	4 (12.5)	1 (12.5)	3 (12.5)	1.000
Pleural effusion requiring drainage	2 (6.3)	2 (25.0)	0 (0)	0.056
Peritoneal effusion requiring drainage	11 (34.4)	5 (62.5)	6 (26.1)	0.095

DHCA, deep hypothermic circulatory arrest; VIS, vasoactive-inotropic score; LOS, length of stay; ICU, intensive care unit.

Cerebral and Renal Oxygenation

The changes in ScO_2 and StO_2 levels were closely monitored throughout the perioperative period. Significant time points were analyzed during the procedure, including on-CPB, aortic cross-clamp-on, aortic cross-clamp-off, off-CPB, and modified ultrafiltration (Table 3). During the operation, ScO_2 decreased at the time points of aortic cross-clamp-off, off-CPB, and modified ultrafiltration compared to preoperative baseline levels. However, StO_2 remained relatively stable during the procedure. The trends in postoperative ScO_2 and StO_2 for both groups are shown in Fig. 2.

Table 3. Changes in ScO_2 and StO_2 at different times during the operation.

	Pre-operation	On-CPB	Cross-clamp-on	Cross-clamp-off	Off-CPB	Modified ultrafiltration
ScO_2 (%), mean (SD)	63.0 (10.5)	62.1 (8.1)	62.7 (7.9)	57.3 (6.1)	56.9 (6.0)	55.0 (7.8)
StO_2 (%), mean (SD)	63.5 (14.7)	60.8 (12.7)	60.1 (10.5)	65.3 (11.8)	61.9 (10.7)	59.3 (10.9)

CPB, cardiopulmonary bypass.

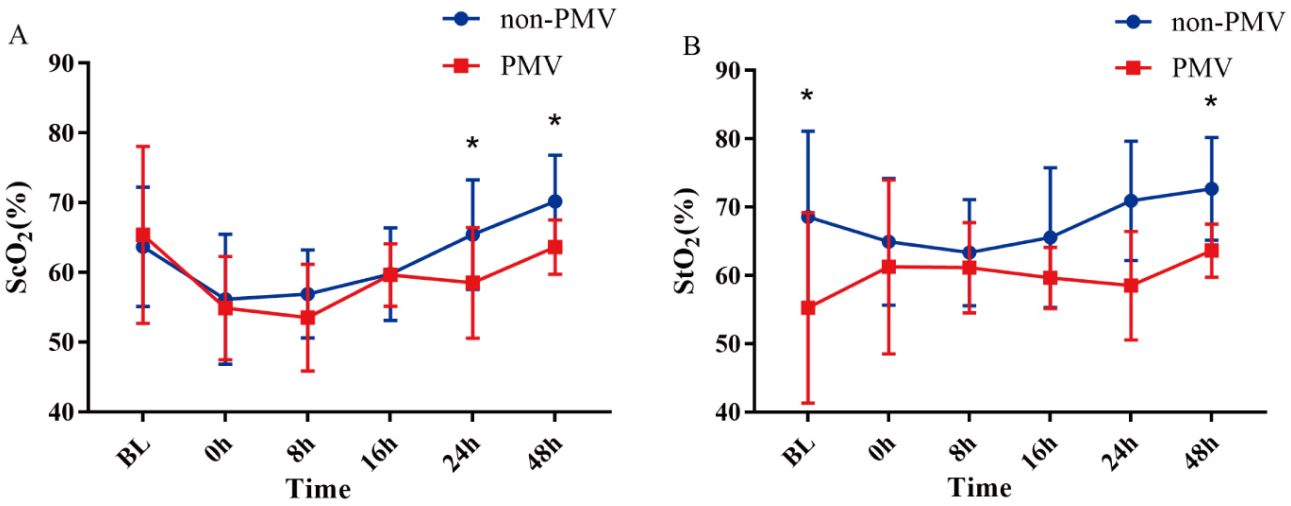

Fig. 2. The changing trends in ScO_2 (A) and StO_2 (B) from 0 to 48 hours postoperatively in the two groups. * $p < 0.05$.

The ScO_2 decreased after surgery from baseline and gradually increased at 8 hours post-operation, nearly reaching preoperative levels by 48 hours. At 24 hours, the PMV group had significantly lower ScO_2 compared to the non-PMV group (58.5 ± 7.9% vs. 65.4 ± 7.9%; $p = 0.040$), and the difference persisted at 48 hours (63.6 ± 3.9% vs. 70.2 ± 6.7%; $p = 0.014$). There was no significant difference in ScO_2 at other time points (Fig. 2A). The StO_2 showed similar trends. Preoperative StO_2 levels were lower in the PMV group compared to the non-PMV group (50.8 ± 14.1% vs. 67.8 ± 12.5%; $p = 0.003$), but StO_2 improved postoperatively in both groups (Fig. 2B).

Cardiac Index and Serum Lactate

The perioperative changes in the CI and serum lactate levels were examined and are presented in Fig. 3. CI decreased significantly after surgery in the non-PMV group. This decline persisted until approximately 8 hours postoperatively, after which the CI gradually increased. In contrast, the PMV group showed a similar initial decline in CI; however, the CI remained relatively low or slightly decreased at 16 hours post-surgery, without the same recovery observed in the non-PMV group. Baseline CI values were higher in the non-PMV group compared to the PMV group. Additionally, the CI rebound occurred more rapidly in the non-PMV group after surgery. The CI in the non-PMV group was significantly higher than in the PMV group at 48 hours post-operation (2.94 ± 0.54 vs. 2.26 ± 0.49; $p = 0.003$) (Table 4). Postoperative serum lactate levels were significantly

Table 4. Post-surgery CI levels.

Time points (hours)	PMV	non-PMV	*p*-value
0 (L/(min × m^2)), mean (SD)	1.97 (0.84)	2.23 (0.44)	0.272
8 (L/(min × m^2)), mean (SD)	2.07 (0.47)	2.09 (0.66)	0.940
16 (L/(min × m^2)), mean (SD)	2.23 (0.50)	2.38 (0.58)	0.549
24 (L/(min × m^2)), mean (SD)	2.34 (0.61)	2.59 (0.51)	0.284
48 (L/(min × m^2)), mean (SD)	2.26 (0.49)	2.94 (0.54)	0.003

higher in the PMV group compared to the non-PMV group at 0 h (3.25 ± 1.31 vs. 1.84 ± 0.96 mmol/L, $p = 0.002$), 4 h (3.65 ± 1.29 vs. 2.25 ± 1.05 mmol/L; $p = 0.019$), and 8 h (4.05 ± 1.30 vs. 2.45 ± 0.91 mmol/L; $p = 0.001$), indicating greater metabolic stress or tissue hypoxia in PMV patients during the early postoperative period. Although the PMV group maintained elevated lactate levels at 12 h and 16 h, the differences were no longer statistically significant ($p = 0.142$ and $p = 0.109$, respectively). By 20 h, the difference between the two groups had narrowed further ($p = 0.062$), and lactate levels were comparable at 24 h (2.69 ± 1.51 vs. 2.35 ± 1.16 mmol/L; $p = 0.511$), suggesting a gradual resolution of metabolic disturbances in PMV patients within 24 hours post-surgery (Table 5).

Discussion

Our exploratory findings are consistent with the hypothesis that delayed CI recovery and persistent tissue hy-

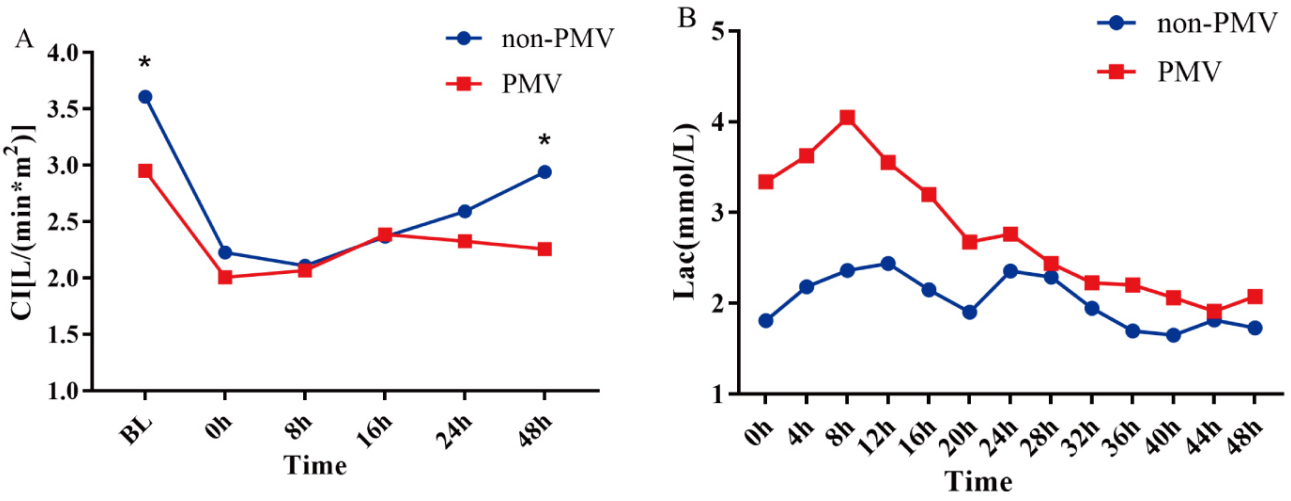

Fig. 3. The changing trends in CI (A) and blood lactate (B) from 0 to 48 hours post-operation in the two groups. Lac, lactate. *$p < 0.05$.

Table 5. Post-operation serum lactate levels.

Time points (hours)	PMV	non-PMV	*p*-value
0 (mmol/L), mean (SD)	3.25 (1.31)	1.84 (0.96)	0.002
4 (mmol/L), mean (SD)	3.65 (1.29)	2.25 (1.05)	0.019
8 (mmol/L), mean (SD)	4.05 (1.30)	2.45 (0.91)	0.001
12 (mmol/L), mean (SD)	3.55 (1.74)	2.50 (1.07)	0.142
16 (mmol/L), mean (SD)	3.20 (1.58)	2.16 (0.74)	0.109
20 (mmol/L), mean (SD)	2.68 (1.17)	1.90 (0.91)	0.062
24 (mmol/L), mean (SD)	2.69 (1.51)	2.35 (1.16)	0.511

poperfusion may contribute to PMV in neonates. The divergence in hemodynamic and oxygenation trajectories between PMV and non-PMV groups was observed as early as 8 hours postoperatively—though based on a limited cohort (n = 32, PMV = 8)—suggesting a potential window for early targeted interventions (e.g., inotropic support, perfusion-guided fluid management). However, owing to the small sample size and inherent variability in neonatal cardiac surgery outcomes, these results should be interpreted as hypothesis-generating rather than definitive evidence. Moreover, further validation in larger, multicenter cohorts is essential to confirm the clinical utility of these hemodynamic patterns in guiding respiratory support strategies.

The perioperative period presents unique challenges for neonates undergoing cardiac surgery, particularly those with congenital heart defects. In this cohort, 31 out of 32 neonates were successfully discharged following surgery, while one newborn died early after the procedure. The most common postoperative complications observed were abdominal effusion requiring drainage (n = 11), followed by arrhythmias requiring medical treatment (n = 6). Additionally, seven neonates required peritoneal dialysis postoperatively.

Previous studies have suggested that neurological damage is a frequent complication during CPB procedures [13]. Razlevice *et al.* [14] proposed that a decrease in ScO_2 from baseline levels of at least 20% may indicate hypoxic brain injury. In our study, the ScO_2 fluctuated significantly during CPB, with a notable decline after removing the aortic cross-clamp. This decrease in cerebral oxygenation could be attributed to multiple factors, including increased cerebral oxygen consumption during rewarming, decreased arterial perfusion pressure, and reduced hematocrit levels due to hemodilution during CPB.

We stratified patients into two groups based on the duration of postoperative mechanical ventilation to improve understanding of the relationship between perioperative oxygenation and clinical outcomes. Our findings revealed that neonates in the PMV group had lower preoperative StO_2 levels compared to the non-PMV group. Postoperatively, all patients experienced some degree of decline in both ScO_2 and StO_2, which could result from a complex interaction of factors, including decreased cardiac output, insufficient circulating blood volume, impaired microcirculation, increased vascular tone, and alterations in the temperature differential between the extremities and the core [15–17]. Notably, both ScO_2 and StO_2 improved over time, with patients in the non-PMV group recovering to baseline levels more rapidly. These observations suggest that if postoperative ScO_2 and StO_2 levels remain low, early investigation into the underlying causes and prompt intervention are critical to expedite recovery.

Impaired cardiac output leading to insufficient tissue oxygenation is a well-established issue after pediatric cardiac surgery, and it is strongly associated with increased morbidity and mortality [18]. Our study observed that the CI reached its nadir approximately eight hours post-surgery and gradually increased thereafter. Similar trends in the CI and lactate levels were reported by Yang *et al.* [19]. Inter-

estingly, there were preoperative differences in the CI between the PMV and non-PMV groups (3.0 ± 0.82 vs. 3.6 ± 0.75; $p = 0.044$). After the surgical shock, recovery rates for the CI differed significantly between the two groups. The non-PMV group demonstrated a substantial improvement in the CI by 48 hours post-surgery. In contrast, the PMV group showed minimal improvement, with the CI remaining close to its 8-hour postoperative values. This suggests that careful monitoring of hemodynamic changes and timely adjustments in treatment regimens are essential for improving postoperative outcomes, particularly in high-risk patients.

Vasoactive drug use, quantified by the VIS, is another important factor associated with patient outcomes, including in-hospital mortality [20]. In our study, the PMV group had a significantly higher VIS compared to the non-PMV group (14.0 [10.3–18.8] vs. 10.0 [8.0–15.0]; $p = 0.038$), which is consistent with the premise that more severe hemodynamic instability may contribute to prolonged mechanical ventilation and worse outcomes.

Blood lactate levels are commonly used to assess tissue perfusion and oxygenation. Elevated lactate levels reflect poor organ perfusion and a shift to anaerobic metabolism [18]. In our cohort, lactate levels peaked around 8 hours post-surgery, particularly in the PMV group. This finding highlights the importance of early detection and management of postoperative metabolic disturbances. Timely intervention to address the underlying causes of elevated lactate can potentially improve prognosis and accelerate recovery, especially within the first 24 hours after surgery.

Several limitations to this study must be acknowledged. First, this is a single-center study with a relatively small sample size, which limits the ability to perform multivariate analyses. Additionally, confounding factors may have influenced the results. Therefore, larger, multi-center studies are warranted to validate our findings. Second, the CI measurements were taken at specific time points after surgery, which may not capture the full dynamic changes in hemodynamics during the perioperative period. Finally, we only investigated the impact of the perioperative CI and rSO_2 changes on short-term postoperative outcomes. Hence, future studies should aim to assess the long-term clinical implications of these parameters, including mid- and long-term patient survival and functional outcomes.

Conclusions

This exploratory cohort study identified delayed CI normalization and sustained tissue hypoperfusion within the critical 48-hour postoperative window as potential predictors of PMV in neonatal cardiac surgical patients. These findings highlight the necessity of multicenter validation studies with expanded sample sizes to establish the prognostic value of early hemodynamic trajectories in optimizing ventilator weaning protocols.

Availability of Data and Materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Author Contributions

YZ: data analysis and writing; HZ: formal analysis; GL: methodology validation; JZ: statistical methodology design; QW: supervision of research design and funding acquisition. All authors read and approved the final manuscript. All authors have participated sufficiently in the work. All authors contributed to editorial changes in the manuscript. All authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Ethics Approval and Consent to Participate

The study was carried out in accordance with the guidelines of the Declaration of Helsinki and approved by the Ethics Committee of Anzhen Hospital, Capital Medical University (No. 2023222X). Written informed consent for publication was obtained from all participants.

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Conflict of Interest

The authors declare no conflict of interest.

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