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Original Article

Predictive value of oxygen delivery and regional oxygen saturation during cardiopulmonary bypass for cardiac surgery-associated acute kidney injury in neonates with congenital heart disease

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Abstract: Objective: To explore the predictive value of intraoperative oxygen delivery (DO_2) and renal regional oxygen saturation (rSO_2) during cardiopulmonary bypass (CPB) for cardiac surgery-associated acute kidney injury (CS-AKI) in neonates with congenital heart disease (CHD). Methods: A total of 235 neonates who underwent CPB-assisted cardiac surgery were enrolled and divided into CS-AKI and non-CS-AKI groups according to the occurrence of postoperative CS-AKI. Perioperative clinical data, intraoperative DO_2 and renal rSO_2 as well as postoperative recovery indicators were collected. Binary logistic regression analysis was performed to screen independent risk factors for CS-AKI. Based on the independent predictors, a predictive nomogram was constructed and validated internally and externally. The predictive value of DO_2 and rSO_2 for CS-AKI was assessed. Results: Aortic cross-clamp (ACC) time, DO_2 at 5 minutes post-ACC (T2), DO_2 at 5 minutes after aortic opening (T3), the minimum renal rSO_2 during CPB (R_min), and renal rSO_2 at CPB termination (R_post) were independent influencing factors for CS-AKI. The combined application of the above four DO_2 and rSO_2 indicators yielded the optimal predictive efficacy for CS-AKI, with an (AUC) of 0.924. The constructed nomogram exhibited good discriminatory power, and external validation confirmed its excellent predictive efficiency. Conclusion: ACC time, DO_2 (T2, T3) and renal rSO_2 (R_min, R_post) were independent determinants of CS-AKI in CHD neonates. The nomogram established based on these intraoperative oxygenation indices achieved superior predictive performance for postoperative CS-AKI.

Keywords: Congenital heart disease, newborns, cardiopulmonary bypass, oxygen delivery, regional oxygen saturation, cardiac surgery-associated acute kidney injury, predictive value

Introduction

Congenital heart disease (CHD) is the most common congenital malformation, characterized by structural abnormalities of the heart or great vessels that develop during the fetal period [1]. Affected infants often develop cyanosis, hypoxia, malnutrition, growth retardation and heart failure, which severely impair their quality of life [2]. Approximately 20% of affected neonates may die without timely clinical intervention [3]. The high mortality is primarily attributed to the immature organ development, poor surgical tolerance, unstable vital signs, complex cardiovascular physiologic and anatomic characteristics of neonates, as well as the high difficulty of surgical operation and postoperative monitoring [4]. Currently, cardiopulmonary bypass (CPB)-assisted cardiac surgery is the preferred treatment for neonatal CHD, which provides a stable and clear surgical field for cardiothoracic surgeons. However, CPB inevitably causes severe physiological disturbances to immature vital organs, blood circulation and immune systems in neonates [5]. Postoperative cardiac surgery-associated acute kidney injury (CS-AKI) is a common and critical complication in CHD children undergoing CPB, with a reported incidence of 52% [6]. Due to immature renal regulatory function, neonates with CHD are highly susceptible to renal ischemia, inflammatory injury and other adverse perioperative

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events, which significantly increase the risk of CS-AKI [7]. At present, studies focusing on CS-AKI predictive indicators in neonates aged 0 to 28 days remain scarce, and the threshold values of biological indicators derived from adult studies are not applicable to the neonatal population. Therefore, it was urgent to explore specific predictive factors for neonatal CS-AKI.

Oxygen delivery (DO_2), calculated as the product of indexed perfusion flow and arterial oxygen content, is a core indicator for evaluating intraoperative perfusion adequacy during CPB [8, 9]. Insufficient DO_2 is closely correlated with severe intraoperative hemodilution and adverse renal outcome after CPB [10]. A previous study by Taka et al. [11] indicated no significant correlation between DO_2-related parameters and CS-AKI in pediatric CHD patients under 15 years old, highlighting the necessity of verifying such an association in neonates aged 0-28 days. Regional oxygen saturation (rSO_2) is monitored in real time by non-invasive near-infrared spectroscopy (NIRS) [12]. Renal rSO_2 monitoring is particularly suitable for patients with hemodynamic instability, enabling early identification of tissue hypoperfusion and renal oxygenation deficiency [13]. A prospective study by Javaherforooshzadeh et al. [14] validated the clinical value of renal rSO_2 in predicting postoperative CS-AKI. Similarly, Bonsante et al. [15] found that low renal rSO_2 on the first postnatal day was associated with acute kidney injury in preterm infants with a gestational age of less than 32 weeks.

Overall, high-quality studies on independent predictors of CS-AKI in neonates undergoing CPB-assisted cardiac surgery are still limited. This study aimed to analyze the predictive value of intraoperative DO_2 and renal rSO_2 for neonatal CS-AKI, so as to provide evidence to optimize intraoperative CPB management and improve renal protection in neonates.

Materials and methods

General information

A total of 235 neonates diagnosed with CHD who underwent CPB-assisted cardiac surgery at Guangzhou Red Cross Hospital from January 2022 to December 2024 were retrospectively enrolled. All subjects were divided into a CS-AKI group (n=118) or a non-CS-AKI group (n=117) according to the presence or absence of postoperative CS-AKI. For model construction, 235 cases with 118 positive CS-AKI events were included. With 10 candidate variables enrolled, the event per variable (EPV) was 11.8 (greater than 10), which met the minimum sample size requirement for clinical prediction models. This retrospective study was approved by the Ethics Committee of Guangzhou Red Cross Hospital.

Case selection criteria

Inclusion criteria: Neonates aged 0-28 days with CHD confirmed by cardiac ultrasonography, magnetic resonance imaging (MRI) or spiral computed tomography (CT) [16]; no contraindications to CPB; no preoperative continuous renal replacement therapy or extracorporeal membrane oxygenation; preoperative hemoglobin (Hb) >100 g/L; preoperative platelet count >100×10^9/L; preoperative serum creatinine (Scr) within the normal range for corresponding postnatal days.

Exclusion criteria: Preoperative renal or intracranial organic lesions, or refractory heart failure; surgery without aortic cross-clamp (ACC) procedure; combined multiple congenital malformations; recent exposure to nephrotoxic drugs including nephrotoxic antibiotics, nonsteroidal anti-inflammatory drugs, angiotensin-converting enzyme inhibitors and contrast agents; concurrent severe systemic infectious diseases; incomplete clinical and research data.

Anesthesia, operation, and CPB management

All neonates received intravenous anesthesia induction and tracheal intubation after entering the operating room. Radial artery and internal jugular vein catheterization was performed after successful general anesthesia. During surgery, 1%-2% sevoflurane was inhaled continuously, combined with intravenous infusion of sufentanil at 2 μg/kg/h and rocuronium at 1 mg/kg/h. A roller pump and membrane oxygenator were applied for CPB. The CPB priming solution consisted of sodium acetate Ringer's solution, 5% sodium bicarbonate, 10% calcium gluconate, red blood cell suspension, heparin, and plasma or hydroxyethyl starch. CPB was initiated when the activated whole blood clotting time exceeded 480 s. The intraoperative mean arterial pressure (MAP) was maintained at 40-60 mmHg. Conventional ultrafiltration

was performed during surgery, and modified ultrafiltration was implemented immediately after CPB termination.

Observation endpoints and indicator detection

Baseline data: Neonatal gender, postnatal age, height, weight, gestational age and preoperative Scr level were collected.

Perioperative clinical indicators: Surgical type, total CPB duration, ACC time, intraoperative hematocrit (Hct), Hb, lactate (Lac), postoperative hypotension and postoperative blood transfusion (PBT) volume were recorded and analyzed.

Detection of DO_2 and rSO_2: For DO_2 detection, arterial blood gas samples were collected at three key intraoperative time points: T1 (before anesthesia induction), T2 (5 minutes after ACC), and T3 (5 minutes after aortic opening). Synchronous CPB pump flow was recorded, and DO_2 was calculated by the standard formula: DO_2 = pump flow × [1.36 × Hb(g/L) × SaO_2(%) + 0.003 × PaO_2(mmHg)]. For renal rSO_2 monitoring, an NIRS monitor was used with the probe placed over the superficial projection area of the right kidney. Renal rSO_2 was continuously monitored from anesthesia induction to the end of surgery, and key data at three time points were recorded: R0 (after anesthesia induction and before CPB initiation), R_min (the minimum rSO_2 value during CPB), and R_post (rSO_2 value at CPB termination).

Postoperative recovery indicators: Postoperative intensive care unit (ICU) stay, total hospital stay, and clinical prognosis were observed and recorded.

Statistical analyses

SPSS 24.0 software was used for all statistical analyses. The Shapiro-Wilk test was applied to verify data normality. Normally distributed measured data were expressed as mean ± standard deviation (SD), and compared by independent sample t-test (inter-group) and paired t-test (intra-group pre- and post-operation). Non-normally distributed measured data were presented as median (interquartile range) [M (Q1, Q3)], and inter-group differences were analyzed by the Mann-Whitney U test. Counted data were described as case number (percentage) [n (%)], and compared using the χ^2 test or Fisher's exact test; the Fisher-Freeman-Halton exact test was adopted for 2×C contingency tables (C≥3). Univariate analysis was first performed to screen differential indicators between groups, and variables with $P<0.05$ were included in binary Logistic regression analysis to identify independent predictors of CS-AKI. Receiver operating characteristic (ROC) curves were plotted to evaluate the predictive efficacy of single and combined indicators. Based on the multivariate regression results, a predictive nomogram was constructed, with internal validation using 1000 bootstrap resamples and external validation in an independent cohort. Calibration curves and ROC curves were used to verify model performance. All statistical tests were two-tailed, and $P<0.05$ was considered significant.

Results

Comparison of baseline data

As shown in **Table 1**, there were no significant inter-group differences in baseline characteristics including gender, postnatal age, height, weight, gestational age and preoperative Scr level between the CS-AKI group and non-CS-AKI group (all $P>0.05$).

Comparison of perioperative clinical indicators

As presented in **Table 2**, surgical type, total CPB duration, ACC time and PBT volume were significantly associated with postoperative CS-AKI (all $P<0.05$), while intraoperative Hct, Hb, Lac and postoperative hypotension showed no significant correlation with CS-AKI (all $P>0.05$).

Comparison of intraoperative DO_2 and renal rSO_2 levels

As shown in **Table 3**, the CS-AKI group had significantly lower DO_2 values at T1, T2 and T3, as well as markedly decreased renal rSO_2 levels at R0, R_min and R_post during surgery compared to the non-CS-AKI group (all $P<0.01$).

Comparison of postoperative recovery outcomes

As shown in **Table 4**, the CS-AKI group had significantly longer ICU stay and total hospital stay than the non-CS-AKI group (both $P<0.001$), and

Table 1. Comparison of baseline data

Data	CS-AKI group (n=118)	Non-CS-AKI group (n=117)	Z/t	P
Male	76 (64.41)	64 (54.70)	2.298	0.130
Age (d)	14.13±6.32	15.13±6.58	1.188	0.236
Height (cm)	43.00 (39.00, 50.00)	44.00 (40.00, 49.00)	-0.779	0.436
Weight (kg)	3191.93±432.62	3208.02±364.51	0.308	0.758
Gestational age (weeks)	39.00 (38.00, 40.00)	38.00 (37.00, 40.00)	-1.341	0.180
Preoperative Scr (μmol/L)	36.58±8.55	33.79±13.38	1.906	0.058

Note: CS-AKI, cardiac surgery-associated acute kidney injury; Scr, serum creatinine.

Table 2. Comparison of perioperative clinical indices

Indicator	CS-AKI group (n=118)	Non-CS-AKI group (n=117)	χ^2/t	P
Type of surgery			7.607	0.006
Low-risk	33 (27.97)	53 (45.30)		
High-risk	85 (72.03)	64 (54.70)		
CPB time (min)	47.86±9.69	42.97±13.97	3.120	0.002
ACC time (min)	29.51±5.41	26.60±4.74	4.384	<0.001
Hct	0.40±0.18	0.44±0.24	1.446	0.150
Hb (g/L)	116.98±18.64	115.43±15.11	0.700	0.485
Lac (g/L)	0.67±0.20	0.70±0.18	1.208	0.228
Postoperative hypotension	33 (27.97)	23 (19.66)	2.234	0.135
Postoperative blood transfusion volume (mL)	236.64±96.27	198.20±81.99	3.294	0.001

Note: CS-AKI, cardiac surgery-associated acute kidney injury; CPB, cardiopulmonary bypass; ACC, aortic cross-clamp; Hct, hematocrit; Hb, hemoglobin; Lac, lactate. Low-risk operations refer to ventricular septal defect repair (VSD)/atrial septal defect repair (ASD)/patent ductus arteriosus ligation/patent ductus arteriosus repair; High-risk procedures include correction of Tetralogy of Fallot/complete atrioventricular septal defect (CAVSD)/arterial switch operation (ASO)/total anomalous pulmonary venous connection (TAPVC)/primary Norwood operation.

Table 3. Comparison of DO_2 and rSO_2

Indicator	CS-AKI group (n=118)	Non-CS-AKI group (n=117)	t	P
DO_2 (mL/min/m^2)				
T1	338.45±47.87	359.22±42.25	3.525	<0.001
T2	278.14±45.54	318.15±48.76	6.501	<0.001
T3	251.50±55.31	325.91±69.74	9.066	<0.001
rSO_2 (%)				
R0	78.20±7.89	81.19±7.14	3.045	0.003
R_min	45.69±12.38	60.18±10.42	9.703	<0.001
R_post	61.53±14.16	74.15±11.29	7.550	<0.001

Note: CS-AKI, cardiac surgery-associated acute kidney injury; DO_2, oxygen delivery; rSO_2, regional oxygen saturation; T1, pre-anesthesia; T2, 5 minutes post-ACC; T3, 5 minutes post-aortic opening; R0, post-anesthesia induction and before CPB initiation; R_min, the lowest value during CPB; R_post, upon CPB cessation.

the overall clinical prognosis of the CS-AKI group was significantly poorer (P=0.011).

Binary logistic regression analysis of CS-AKI influencing factors

All indicators with significant inter-group differences in univariate analysis were included in the binary Logistic regression model. The results showed that surgical type, total CPB duration, PBT volume, DO2_T1 and rSO2_R0 were not independent influencing factors for CS-AKI (all P>0.05). In contrast, ACC time, DO_2_T2, DO_2_T3, rSO_2_R_min and rSO_2_R_post were independent predictors of CS-AKI (all P<0.05) (**Table 5**).

Table 4. Comparison of postoperative recovery

Indicator	CS-AKI group (n=118)	Non-CS-AKI group (n=117)	Z/t	P
ICU stay (d)	8.00 (5.75, 11.00)	4.00 (3.00, 6.00)	-8.225	<0.001
Total hospital stay (d)	17.70±7.61	11.87±4.26	7.238	<0.001
Clinical outcome			Fisher's exact test	0.011
Cured	98 (83.05)	111 (94.87)		
Dead	4 (3.39)	1 (0.85)		
Life-support	16 (13.56)	5 (4.27)		

Note: CS-AKI, cardiac surgery-associated acute kidney injury; ICU, intensive care unit.

Table 5. Binary logistic regression analysis of CS-AKI influencing factors

Indicator	B	SE	WALD	P	OR	95% CI
Type of surgery	0.060	0.455	0.018	0.895	1.062	0.435-2.590
CPB time (min)	0.023	0.017	1.852	0.174	1.023	0.990-1.058
ACC time (min)	0.097	0.047	4.251	0.039	1.102	1.005-1.208
Postoperative blood transfusion volume (mL)	0.003	0.002	1.370	0.242	1.003	0.998-1.007
DO_2_T1 (mL/min/m^2)	-0.006	0.005	1.560	0.212	0.994	0.985-1.003
DO_2_T2 (mL/min/m^2)	-0.013	0.005	7.492	0.006	0.987	0.978-0.996
DO_2_T3 (mL/min/m^2)	-0.018	0.004	19.414	<0.001	0.982	0.974-0.990
rSO_2_R0 (%)	-0.053	0.029	3.344	0.067	0.948	0.896-1.004
rSO_2_R_min (%)	-0.081	0.019	17.619	<0.001	0.923	0.889-0.958
rSO_2_R_post (%)	-0.067	0.018	14.117	<0.001	0.935	0.902-0.968

Note: CS-AKI, cardiac surgery-associated acute kidney injury; CPB, cardiopulmonary bypass; ACC, aortic cross-clamp; DO_2, oxygen delivery; rSO_2, regional oxygen saturation; SE, Standard Error; OR, Odds Ratio; CI, Confidence Interval; T1, pre-anesthesia; T2, 5 minutes post-ACC; T3, 5 minutes post-aortic opening; R0, post-anesthesia induction and before CPB initiation; R_min, the lowest value during CPB; R_post, upon CPB cessation.

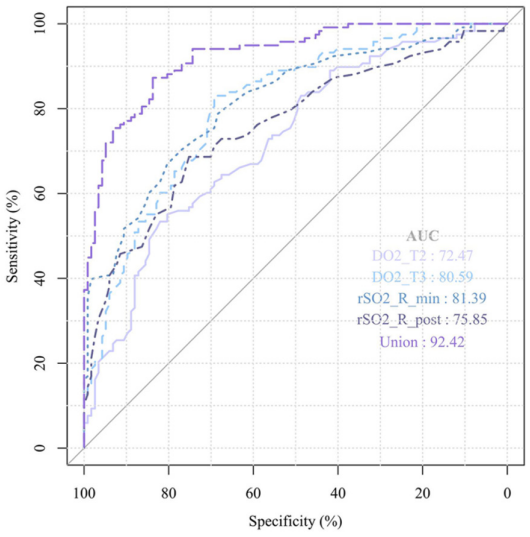

Figure 1. ROC curve of CS-AKI predicted by DO_2 and rSO_2. ROC, Receiver operating characteristic; CS-AKI, cardiac surgery-associated acute kidney injury; DO_2, oxygen delivery; rSO_2, regional oxygen saturation; T2, 5 minutes post-ACC; T3, 5 minutes post-aortic opening; R_min, the lowest value during CPB; R_post, upon CPB cessation.

Predictive efficacy of DO_2 and rSO_2 for CS-AKI

The ROC curve analysis results of single and combined indicators for predicting CS-AKI are shown in **Figure 1** and **Table 6**. For DO_2_T2, the AUC was 0.725 (95% CI: 0.661-0.789, P< 0.001); at the optimal cut-off value of 279.00 mL/min/m^2, the sensitivity was 53.39% and the specificity was 82.05%. DO_2_T3 yielded an AUC of 0.806 (95% CI: 0.751-0.861, P< 0.001), with an optimal cut-off value of 295.50 mL/min/m^2, corresponding to a sensitivity of 83.05% and a specificity of 69.23%. For rSO_2_R_min, the AUC was 0.814 (95% CI: 0.760-0.868, P<0.001); the optimal cut-off value was 51.50%, with a sensitivity of 66.95% and a specificity of 80.34%. rSO_2_R_post had an AUC of 0.759 (95% CI: 0.697-0.820, P<0.001), with an optimal cut-off value of 66.50%, a sensitivity of 68.64% and a specificity of 75.21%. The combination of DO_2_T2, DO_2_T3, rSO_2_R_min and rSO_2_R_post achieved the highest AUC of 0.924 (95% CI: 0.892-

Table 6. Predictive value of DO_2 and rSO_2 for CS-AKI

Indicator	AUC	95% CI	P	Optimal cut-off	Sensitivity	Specificity
DO_2_T2 (mL/min/m^2)	0.725	0.661-0.789	<0.001	279.00	53.39%	82.05%
DO_2_T3 (mL/min/m^2)	0.806	0.751-0.861	<0.001	295.50	83.05%	69.23%
rSO_2_R_min (%)	0.814	0.760-0.868	<0.001	51.50	66.95%	80.34%
rSO_2_R_post (%)	0.759	0.697-0.820	<0.001	66.50	68.64%	75.21%
Combined	0.924	0.892-0.957	<0.001	0.48	87.29%	83.76%

Note: CS-AKI, cardiac surgery-associated acute kidney injury; DO_2, oxygen delivery; rSO_2, regional oxygen saturation; T2, 5 minutes post-ACC; T3, 5 minutes post-aortic opening; R_min, the lowest value during CPB; R_post, upon CPB cessation.

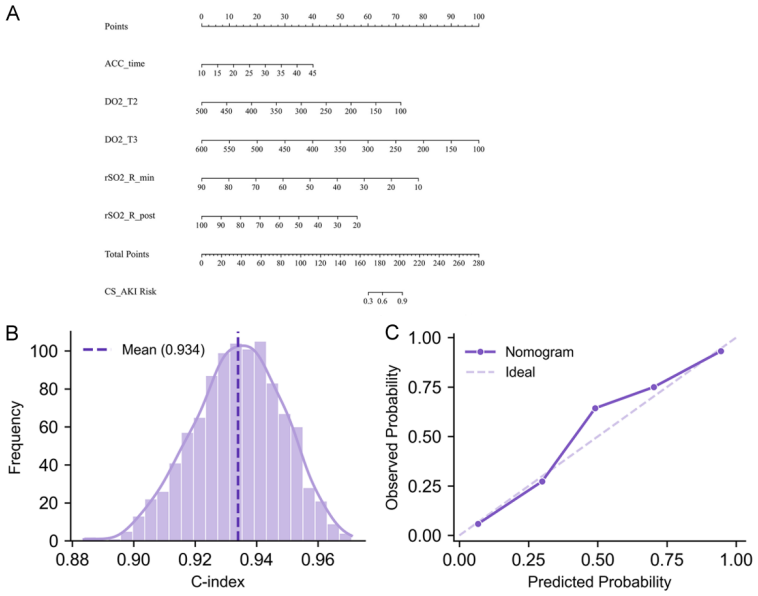

Figure 2. Construction of a nomogram for predicting CS-AKI occurrence probabilities and internal validation. A. Nomogram construction for predicting the occurrence probability of CS-AKI in neonates with CHD. B. Model discrimination validation with 1000 bootstrap repetitions. C. Calibration curve plot. Note: CHD, congenital heart disease; CS-AKI, cardiac surgery-associated acute kidney injury; ACC, aortic cross-clamp; DO_2, oxygen delivery; rSO_2, regional oxygen saturation; T2, 5 minutes post-ACC; T3, 5 minutes post-aortic opening; R_min, the lowest value during CPB; R_post, upon CPB cessation.

0.957, P<0.001), with a sensitivity of 87.29% and a specificity of 83.76% at the optimal cut-off value of 0.48.

Nomogram construction and internal validation

A predictive nomogram for neonatal CS-AKI was established based on the five independent predictors (ACC time, DO_2_T2, DO_2_T3, rSO_2_R_min, rSO_2_R_post) (**Figure 2**). Internal validation showed that the C-index of the model was 0.934 (95% CI: 0.905-0.960), indicating excellent discriminatory ability. Calibration curve analysis revealed that the predictive probability of the model was highly consistent with the actual CS-AKI incidence in low-risk and high-risk populations, while a slight underestimation was observed in the medium-risk population.

External validation of the nomogram

Due to the limitation of single-center sample size, a total of 150 consecutive eligible neonates enrolled from January to December 2025 were included as the external validation cohort. Baseline demographic, renal functional and surgical characteristics (gender, postnatal age, height, weight, gestational age, preoperative Scr, surgical type, total CPB duration and PBT volume) were compared between the training cohort and external validation cohort to verify baseline homogeneity. Indicators including ACC time, intraoperative Hct, Hb and Lac were excluded from baseline comparison, as these are dynamic intraoperative factors affected by surgical procedures and clinical management, rather than fixed baseline characteristics. As shown in **Table 7**, there were no significant differences in baseline clinical data between the two cohorts (all P>0.05). The externally validated nomogram exhibited excellent discriminatory power for CS-AKI, with an AUC of 0.957 (95% CI: 0.926-0.980, **Figure 3**).

Table 7. Comparison of clinical data between external validation and training groups

Data	External validation group (n=150)	Training group (n=235)	χ^2/t	P
Male	95 (63.33)	140 (59.57)	0.544	0.461
Age (d)	14.53±5.59	14.63±6.46	0.156	0.876
Height (cm)	44.07±4.12	44.42±5.53	0.666	0.506
Weight (kg)	3233.30±347.91	3199.94±399.39	0.840	0.402
Gestational age (weeks)	38.69±1.07	38.68±1.33	0.077	0.938
Preoperative Scr (μmol/L)	34.27±10.71	35.19±11.28	0.796	0.427
Type of surgery			0.868	0.351
Low-risk	62 (41.33)	86 (36.60)		
High-risk	88 (58.67)	149 (63.40)		
CPB time (min)	45.27±9.51	45.42±12.24	0.128	0.899
Postoperative blood transfusion volume (mL)	209.80±98.44	217.50±91.31	0.783	0.434

Note: Scr, serum creatinine; CPB, cardiopulmonary bypass.

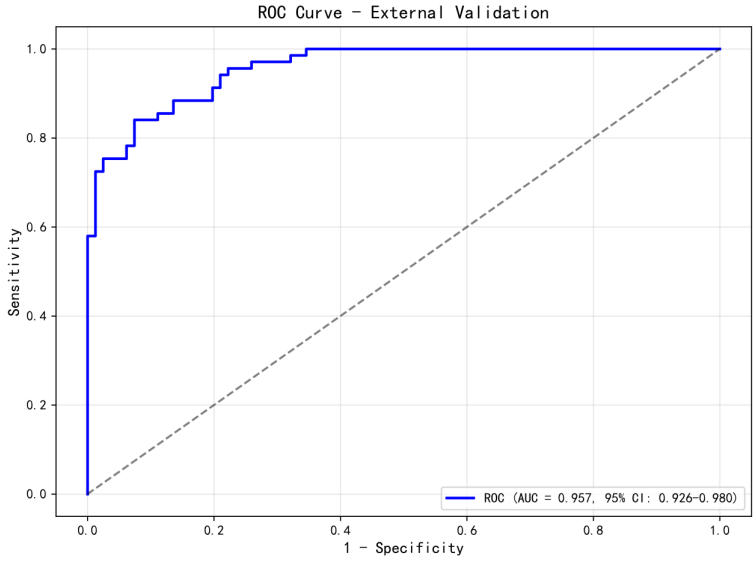

Figure 3. ROC curve analysis of CS-AKI predicted by the external validation set. ROC, Receiver operating characteristic; CS-AKI, cardiac surgery-associated acute kidney injury.

Discussion

The present study found that high-risk surgical types, prolonged CPB duration and ACC time, and increased PBT volume were closely associated with postoperative CS-AKI in CHD neonates. Complex high-risk cardiac surgeries involve difficult anatomic reconstruction, which easily induces severe systemic inflammatory response syndrome and acute hemodynamic fluctuations in neonates, thereby exacerbating ischemia-reperfusion injury and perfusion disturbance in immature renal tissues and increasing CS-AKI risk [17, 18]. Prolonged CPB duration extends the contact time between blood components and artificial circuit surfaces, triggering endothelial dysfunction and tubular toxic injury in neonatal kidneys, which further promotes the occurrence of CS-AKI [19]. Longer ACC time leads to sustained ischemia of systemic organs including the kidneys, and the aggravated inflammatory cascade after reperfusion damages renal tubular epithelial cells, ultimately elevating CS-AKI incidence [20]. Excessive perioperative blood transfusion increases systemic circulatory burden and inflammatory stress, which is an important predisposing factor for renal injury [21]. In addition, this study confirmed that decreased intraoperative DO_2 and renal rSO_2 levels were closely correlated with CS-AKI in neonates. Mechanistically, insufficient systemic oxygen delivery and local renal oxygenation deficiency can aggravate renal oxidative stress and inflammatory responses, exacerbating irreversible damage to immature neonatal kidneys and driving CS-AKI progression [22, 23]. In terms of postoperative prognosis, neonates with CS-AKI had significantly longer ICU and total hospital stays and poorer clinical out-

comes, confirming that CS-AKI severely hinders postoperative recovery of CHD neonates. It is of great clinical significance to explore effective predictive indicators for CS-AKI to implement early intervention and renal protection.

Multivariate Logistic regression analysis further identified prolonged ACC time as an independent risk factor for CS-AKI, while higher DO_2_T2, DO_2_T3, rSO_2_R_min and rSO_2_R_post were independent protective factors against CS-AKI. The loss of statistical significance of surgical type, CPB duration and PBT volume in multivariate analysis may be attributed to the fact that their effects on renal function are indirectly mediated by direct intraoperative oxygenation indicators (DO_2 and rSO_2). Intraoperative DO_2 and renal rSO_2 levels directly reflect systemic oxygen transport capacity and local renal microcirculation oxygen reserve during ischemia and reperfusion. Specifically, a higher DO_2_T2 value indicates sufficient systemic oxygen supply at the early stage of aortic occlusion, which helps resist subsequent renal reperfusion injury. Elevated DO_2_T3 reflects adequate oxygen transport during the early reperfusion period, facilitating the repair of injured renal tubular cells. Higher rSO_2_R_min represents better renal microcirculation perfusion and oxygen reserve during the hypoperfusion stage of CPB, while higher rSO_2_R_post indicates effective recovery of renal oxygenation after CPB termination, both of which are critical for renal protection. Alghamdi et al. [24] reported that low preoperative Scr, high vasoactive inotropic score and prolonged CPB duration were independent risk factors for postoperative AKI in neonates undergoing thoracic surgery, which partially supports our findings. Zhang et al. [25] also confirmed that CPB duration and minimum intraoperative DO_2 were independent influencing factors for CS-AKI in infants with CHD, consistent with our results. Moreover, Shi et al. [26] found that surgical age, cyanotic type, CPB duration over 120 minutes, ACC time, baseline albumin and Scr levels affected CS-AKI in pediatric patients, which further complements the conclusions of this study.

ROC analysis showed that among single indicators, DO_2_T2 had the highest specificity (82.05%), DO_2_T3 had the optimal sensitivity (83.05%), and rSO_2_R_min had the largest AUC value (0.814). The combination of the four oxygenation indicators achieved the best predictive performance (AUC=0.924) with balanced sensitivity and specificity. The present study identified the optimal threshold values for clinical reference: maintaining DO_2_T2 >279.00 mL/min/m^2, DO_2_T3 >295.50 mL/min/m^2, rSO_2_R_min >51.50% and rSO_2_R_post >66.50% can effectively reduce CS-AKI risk in CHD neonates. Dreher et al. [27] proposed that maintaining intraoperative DO_2 above 340 mL/min/m^2 could reduce CS-AKI risk in infants under 1 year old. The discrepancy in threshold values may stem from different monitoring time points: the previous study adopted the average DO_2 level throughout stable CPB, while this study focused on key time points of ischemia and reperfusion, which are more sensitive to renal injury prediction. The newly constructed nomogram covered a wide risk prediction range of 30%-90%. Internal validation verified its excellent discriminatory ability for high-risk and low-risk CS-AKI patients, with only mild underestimation in medium-risk cases. Furthermore, external validation confirmed the robust generalizability and excellent predictive efficacy of the model, providing a novel and practical tool for clinical preoperative and intraoperative CS-AKI risk assessment.

This study has several limitations. First, the sample size of the external validation cohort is limited; future multi-center, large-sample prospective studies are required to further verify the generalizability of the predictive model. Second, the clinical confounding factors affecting intraoperative DO_2 and rSO_2 levels were not analyzed, and prospective studies are needed to clarify the independent predictive value and influencing factors of the two indicators. Third, this study did not explore the interaction effect between ACC time and DO_2/rSO_2 indicators; further research can focus on the combined predictive value of these values for CS-AKI.

In conclusion, prolonged ACC time and decreased intraoperative DO_2 (T2, T3) and renal rSO_2 (R_min, R_post) levels are independent risk factors for CS-AKI in CHD neonates undergoing CPB. As real-time dynamically monitored intraoperative indicators, DO_2 and rSO_2 can realize early warning of postoperative renal injury. The combination of the four oxygenation indicators achieves excellent predictive effica-

cy for CS-AKI. The constructed nomogram has superior discriminatory power and good clinical generalizability, which can accurately identify neonates at high-risk and low-risk of CS-AKI. In future clinical practice, this nomogram can be integrated into electronic medical record systems and intraoperative monitoring platforms to realize real-time CS-AKI risk early warning, guide individualized intraoperative renal protection strategies and optimize perioperative management of CHD neonates, providing reliable evidence for clinical precision treatment.

Disclosure of conflict of interest

None.

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