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Development and validation of a nomogram for predicting perioperative transfusion in children undergoing cardiac surgery with CPB

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Abstract

Background Timely recognition of perioperative red blood cell transfusion (PRT) risk is crucial for developing personalized blood management strategies in pediatric patients. In this study, we sought to construct a prediction model for PRT risk in pediatric patients undergoing cardiac surgery with cardiopulmonary bypass (CPB).

Methods From September 2014 to December 2021, 23,884 pediatric patients under the age of 14 were randomly divided into training and testing cohorts at a 7:3 ratio. Variable selection was performed using univariate logistic regression and least absolute shrinkage and selection operator (LASSO) regression. Multivariate logistic regression was then used to identify predictors, and a nomogram was developed to predict PRT risk. The model's performance was evaluated based on discrimination, calibration, and clinical utility in both cohorts.

Results After multiple rounds of variable selection, eight predictors of PRT risk were identified: age, weight, preoperative hemoglobin levels, presence of cyanotic congenital heart disease, CPB duration, minimum rectal temperature during CPB, CPB priming volume, and the use of a small incision. The predictive model incorporating these variables demonstrated strong performance, with an area under the curve (AUC) of 0.886 (95% CI: 0.880–0.891) in the training cohort and 0.883 (95% CI: 0.875–0.892) in the testing cohort. The calibration plot closely aligned with the ideal diagonal line, and decision curve analysis indicated that the model provided a net clinical benefit.

Conclusions Our predictive model exhibits good performance in assessing PRT risk in pediatric patients undergoing cardiac surgery with CPB, providing clinicians a practical tool to optimize individualized perioperative blood management strategies for this vulnerable population.

Keywords Nomogram, Pediatric, Cardiac surgery, Cardiopulmonary bypass, Perioperative red blood cell transfusion

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Introduction

Pediatric cardiac surgery requiring cardiopulmonary bypass (CPB) is associated with a higher rate of blood transfusions, and perioperative red blood cell transfusion (PRT) remains a critical component of pediatric cardiac care. Unlike in adults, avoiding blood transfusions in pediatric cardiac surgery is significantly more challenging due to several factors, including the increased complexity of surgical procedures, intricate cardiopulmonary dynamics, inadequate oxygen delivery, a higher risk of postoperative bleeding, smaller patient size, and greater metabolic and oxygen demands. As a result, managing PRT in this population presents unique and considerable challenges [1].

Red blood cell (RBC) transfusion has long been a cornerstone of healthcare systems worldwide, with approximately 118 million units of blood collected globally each year. However, this practice also comes with significant costs [2]. In recent years, challenges in maintaining adequate blood supply reserves have emerged due to a decline in the number of blood donors, instances of inappropriate blood use, and insufficient adherence to strict transfusion guidelines. The COVID-19 pandemic has further intensified these challenges [3]. Proactively predicting the need for PRT can improve treatment efficiency, reduce unnecessary economic burdens on patients, minimize the wastage of blood resources, and enhance patient satisfaction. The decision to transfuse RBCs is complex and influenced by a variety of factors. By predicting PRT risk, clinicians can implement optimal blood management strategies [4] and reduce variability in transfusion practices [5]. While RBC transfusions offer benefits such as increased oxygen-carrying capacity, improved tissue oxygenation, and better hemostasis, these advantages must be carefully weighed against potential risks. As a result, there has been increasing focus on identifying high-risk patients who may require PRT prior to surgery. This approach, combined with the use of blood conservation strategies and close monitoring, aims to deliver personalized medical care and maximize cost-effectiveness.

Currently, there is a lack of clinical predictive models based on large-sample data to assess PRT risk in pediatric patients undergoing open-heart surgery with CPB. Identifying high-risk groups and implementing targeted measures is essential to improve outcomes. Therefore, this retrospective analysis aimed to develop a predictive model for PRT risk, with the goal of enhancing PRT management and optimizing care for this vulnerable population.

Method

Study design and population

Given that our center primarily admits children under the age of 14, this retrospective study, conducted at Fuwai Hospital in Beijing, China, focused on pediatric patients younger than 14 years who underwent cardiac surgery involving CPB between September 2014 and December 2021. Eligible participants were those who met the aforementioned criteria. Patients were excluded for the following reasons: a history of heart transplantation, procedures performed without CPB, and incomplete data. The study was approved by the Institutional Review Board (IRB) of Fuwai Hospital, Beijing, China (Approval No. 2023–2265). Due to the retrospective nature of the study, the IRB waived the requirement for written informed consent. This manuscript was prepared in accordance with the relevant TRIPOD guidelines.

Clinical practice of PRT

The PRT practice is conducted as follows:

1. RBC transfusion protocol: (1) Neonates: Transfusion is indicated if Hb levels are < 80 g/L during CPB or < 120 g/L after ultrafiltration or reinfusion of residual pump blood and washed RBCs; (2) age < 1 year old: Transfusion is indicated if Hb levels are < 75 g/L during CPB or < 100 g/L after ultrafiltration or reinfusion of residual pump blood and washed RBCs; (3) age 1–7 years old: Transfusion is indicated if Hb levels are < 75 g/L during CPB or < 90 g/L after ultrafiltration or reinfusion of residual pump blood and washed RBCs; (4) age 7–14 years old: Transfusion is indicated if Hb levels are < 70 g/L during CPB or < 80 g/L after ultrafiltration or reinfusion of residual pump blood and washed RBCs; (5) Postoperative pediatric intensive care unit (PICU) Transfusion is indicated if Hb levels are < 90 g/L.
2. Intraoperative cell salvage: Intraoperative cell salvage is routinely performed to conserve blood.
3. RBC priming conditions: RBCs are added to the priming solution if the patient's weight is < 8 kg or if preoperative Hb levels are < 120 g/L.
4. Ultrafiltration before reinfusion of residual pump blood: Ultrafiltration is performed prior to the reinfusion of residual pump blood to optimize blood quality and reduce unnecessary volume.

Data collection and definition

The following clinical information was collected for each patient: demographic characteristics (sex, age, weight, gestational age, and prematurity); preoperative variables (emergency surgery, Society of Thoracic Surgeons-European Association for Cardio-Thoracic Surgery (STAT) mortality risk score ≥ 3, cyanotic congenital heart disease (CCHD), history of blood transfusion, previous cardiac surgery, preoperative blood transfusion); preoperative laboratory tests (Hb, hematocrit [Hct], creatinine); type of congenital cardiac surgery and surgical incision method; and intraoperative variables (CPB duration, minimum rectal temperature during CPB, CPB priming volume). For patients with multiple hospitalizations, only the first admission record was included. All data were obtained from the hospital's electronic medical record system.

PRT was defined as the administration of RBC during the entire hospital stay, encompassing the operating room, PICU, and postoperative ward. The risk stratification of each surgery was conducted using the STAT score, with STAT 1 denoting the lowest mortality risk and STAT 5 representing the highest mortality risk [6]. The definition of CCHD was based on the anatomy of congenital heart disease, including tetralogy of fallot (TOF), double outlet right ventricle (DORV), pulmonary stenosis (PS), pulmonary atresia (PA), transposition of the great arteries (TGA), tricuspid atresia (TA), single ventricle (SV), total anomalous pulmonary venous connection (TAPVC), complete endocardial cushion defect (CECD), corrected transposition of the great arteries (CTGA), interruption of aortic arch (IAA). The identification of potential high-risk parameters, identified during univariate analysis, was derived from our prior research on factors related to transfusions, clinical experience, and relevant reports.

Establishment and evaluation of the predictive model

The patient cohort was randomly divided, with 70% allocated for the establishment of the nomogram and 30% reserved for testing. Predictors of PRT were initially identified through univariate logistic regression. Subsequently, significant variables were further refined using least absolute shrinkage and selection operator (LASSO) regression. LASSO, a regression technique employing L1-norm penalization, applies a penalty to regression coefficients to improve prediction accuracy and reduce the risk of overfitting. Following this, multivariate logistic regression was performed, incorporating factors with non-zero coefficients derived from LASSO, to develop the prediction model and nomogram. To utilize the predictive model, the value for each variable corresponding to a patient is located on the respective axis. A perpendicular line is then drawn upward to determine the points assigned to that value. The total points are calculated and located on the "Total Points" axis. Finally, a perpendicular line is drawn from the "Total Points" axis to the "PRT Risk" axis to estimate the level of risk.

The discriminative ability and calibration of the model were appraised through the area under the receiver operating characteristic curve (ROC-AUC) and calibration curves, respectively [7]. The clinical utility and net benefit were evaluated via decision curve analysis (DCA).

Besides, we classified the PRT risk score into low, intermediate, and high-risk, following established criteria for classifying the likelihood of transfusions in clinical practice.

Statistical analysis

For continuous variables with missing values constituting less than 5%, the default imputation method involved replacing them with the median value. The distribution of continuous variables was assessed using histograms and Q-Q plots. If the continuous data followed a normal distribution, it was analyzed using a t-test; otherwise, the Mann-Whitney U test was applied. Categorical variables were expressed as frequencies and percentages and were analyzed using the $\chi 2$ test or Fisher's exact test, as appropriate. Propensity score matching (PSM) was performed using 1:1 nearest neighbor matching to adjust for baseline differences between the groups. The caliper value was set to 0.2 for matching participants. The standardized mean difference (SMD) was calculated to evaluate the balance within the model, with an SMD greater than 0.1 indicating imbalance. To validate the calibration of the model, 1000 iterations of bootstrap resampling were conducted in both the training and testing cohorts. All statistical analyses were performed using R version 4.2.1, with a significance threshold of $p < 0.05$ denoting statistical significance.

Results

General characteristics

Between September 2014 and December 2021, 23,884 pediatric patients undergoing cardiac surgery with CPB were evaluated for inclusion in the study. Of these, 4,729 were excluded for the following reasons: absence of CPB ($n = 4{,}048$), heart transplantation ($n = 22$), and incomplete data ($n = 659$). Consequently, 19,155 patients (9,999 males and 9,156 females) were included in the final analysis (Fig. 1). The demographic and clinical characteristics of these participants are detailed in Supplementary Table 1. The patients were randomly allocated into a training cohort ($n = 13{,}408$) and a testing cohort ($n = 5{,}747$). The baseline characteristics of the training and testing cohorts are presented in Supplementary Table 2, demonstrating comparability between the two groups. Among the included subjects, 11,782 (61.5%) were identified as requiring PRT, with 8,290 (61.8%) in the training cohort and 3,492 (60.8%) in the testing cohort.

Clinical outcomes of patients with and without PRT

The clinical characteristics of patients who received and did not receive RBC transfusions, both before and after PSM, are detailed in Supplementary Tables 3 and 4. Supplementary Table 5 summarizes the clinical outcomes for the two groups following PSM. The analysis revealed that perioperative RBC transfusion was associated with a significant increase in chest drainage volume, prolonged

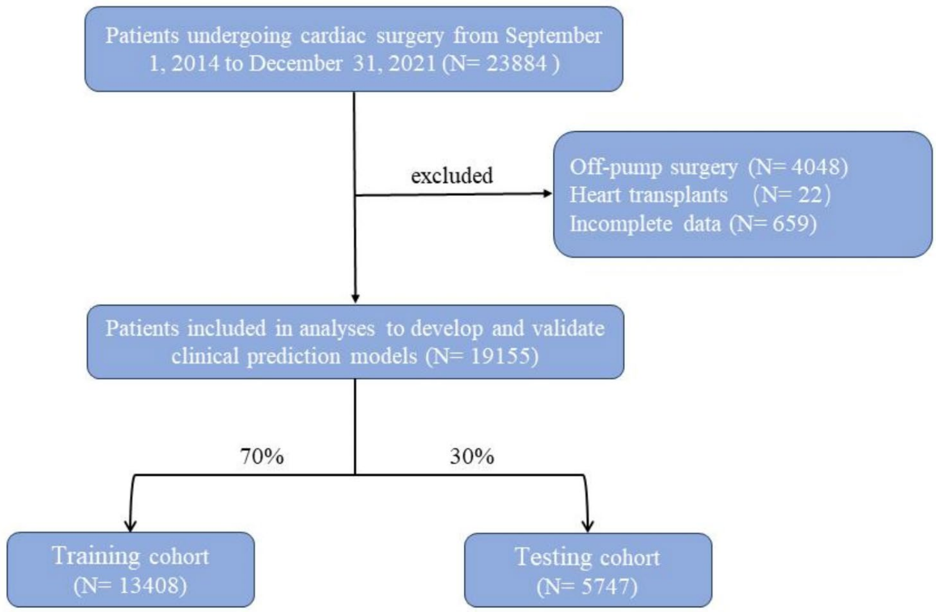

Fig. 1 Flowchart of patient selection for the study

mechanical ventilation time, and a higher incidence of the following outcomes: PICU stay > 5 days, postoperative hospital stay > 7 days, liver injury, acute kidney injury (AKI), postoperative chest drainage volume > 1000 mL, and mechanical ventilation time exceeding 72 h.

Predictive factors screening

The baseline characteristics of patients with and without PRT in the training cohort are presented in Supplementary Table 6. Univariate logistic regression analysis identified 14 out of 16 clinical parameters significantly associated with PRT ($p < 0.1$), as detailed in Supplementary Table 7. Subsequently, the LASSO regression algorithm was applied to further refine variable selection in the training cohort. LASSO regression identified eight predictive parameters with non-zero coefficients from the initial 14 variables, including age, weight, preoperative hemoglobin, CCHD, CPB duration, minimum rectal temperature during CPB, CPB priming volume, and small incision (Fig. 2 and Supplementary Table 8). Multivariate logistic regression analysis was then conducted to determine the predictors of PRT. As shown in Supplementary Table 9, the following eight variables were identified as significant predictors: age (odds ratio [OR], 0.781; 95% confidence interval [CI], 0.746–0.817; $p < 0.001$), weight (OR, 0.964; 95% CI, 0.948–0.981; $p < 0.001$), preoperative Hb (OR, 0.959; 95% CI, 0.955–0.962; $p < 0.001$), CCHD (OR, 1.355; 95% CI, 1.184–1.552; $p < 0.001$), CPB duration (OR, 1.010; 95% CI, 1.009–1.012; $p < 0.001$), minimum rectal temperature during CPB (OR, 0.822; 95% CI, 0.794–0.851; $p < 0.001$), CPB priming volume (OR, 1.037; 95% CI, 1.033–1.042; $p < 0.001$), and small incision (OR, 0.513; 95% CI, 0.463–0.569; $p < 0.001$).

Development of the risk prediction model

A nomogram was developed (Fig. 3) using the eight identified parameters (Supplementary Table 6). For each patient, the total points were calculated by summing the individual scores assigned to each parameter based on their respective point scales. Higher total scores indicated an increased risk of PRT. For example, consider a 5-year-old child with CCHD and endocarditis, weighing 20 kg, with a preoperative hemoglobin level of 110 g/L, CPB duration of 100 min, a minimum rectal temperature during CPB of 30 °C, CPB priming volume of 60 mL/kg, and a median sternotomy. This patient would receive approximate scores of 1, 10, 13, 33, 5, 8, 10, and 2.5 for each parameter, respectively. The total score of approximately 82.5 points corresponds to a predicted PRT risk of 90%.

Predictive performance

The nomogram demonstrated strong predictive performance, with a receiver operating characteristic area under the curve (ROC-AUC) of 0.886 (95% CI: 0.880–0.891) in the training cohort and 0.883 (95% CI: 0.875–0.892) in the testing cohort (Fig. 4A and B). In the training cohort, the sensitivity, specificity, accuracy, positive predictive value (PPV), and negative predictive value (NPV) were 80.4%, 83.9%, 82.2%, 89.0%, and 72.5%, respectively. Similarly, in the testing cohort, these values were 84.2%, 80.0%, 82.1%, 87.0%, and 78.6%. The calibration curves for both the training and testing cohorts closely aligned

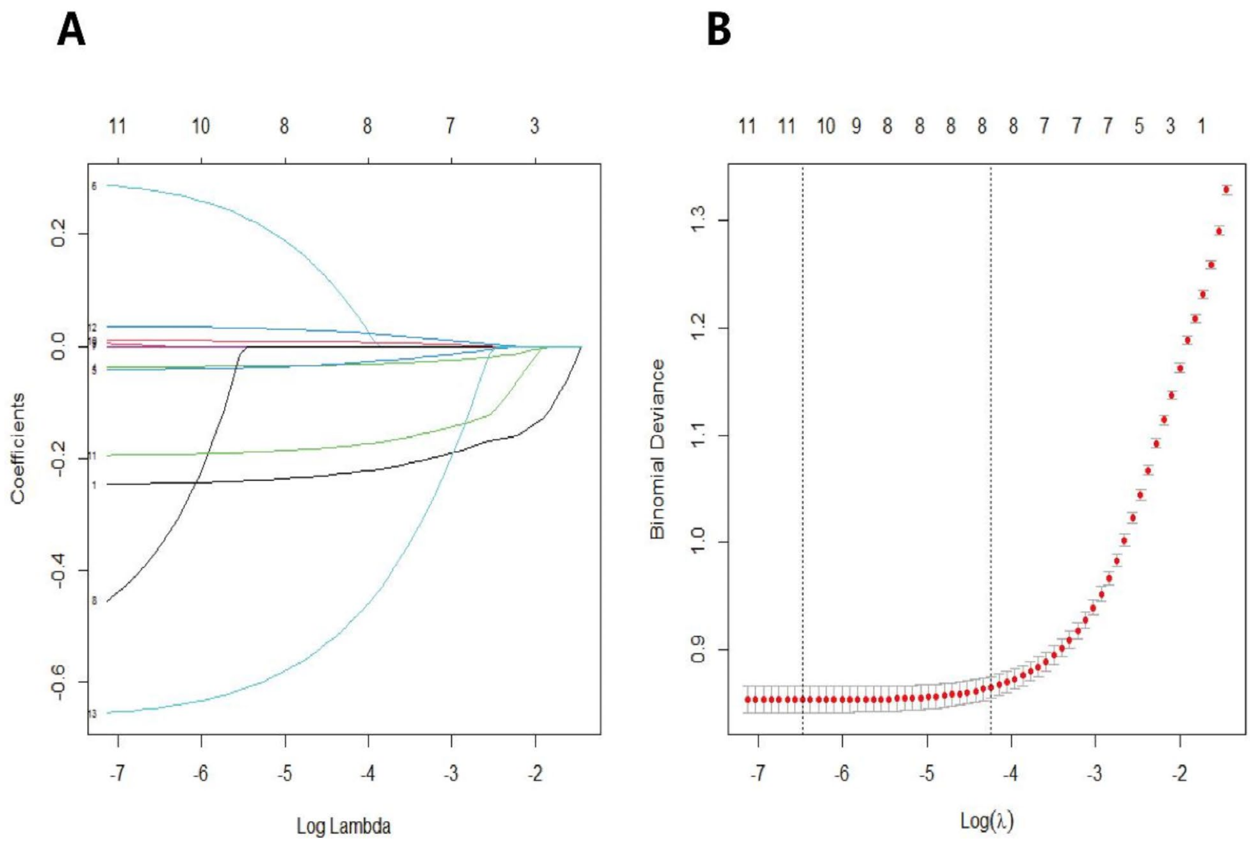

Fig. 2 Predictor selection using logistic LASSO regression. (**A**) Optimal parameter (lambda) selection in the LASSO regression was performed using tenfold cross-validation based on the minimum criteria. (**B**) LASSO coefficient profiles of all variables. A coefficient profile plot was generated against the log(lambda) sequence. A dotted vertical line indicates the value selected using tenfold cross-validation. Seven variables with nonzero coefficients were selected by the optimal lambda (using the 1-SE criteria). LASSO, least absolute shrinkage and selection operator

with the ideal diagonal line, indicating excellent agreement between predicted and observed outcomes (Fig. 4C and D). In addition, decision curve analysis highlighted the clinical utility of the predictive model. The PRT prognostic nomogram (blue) line showed a higher net benefit compared to the "Treat All" (red line) or "Treat None" (green line) strategies, underscoring its value in guiding clinical decision-making (Fig. 4E and F).

Risk stratification

To facilitate clinical implementation, each patient was assigned a risk score based on the predicted values derived from the nomogram, and the corresponding PRT risk was calculated. The risk scores were categorized into three groups: low-risk (PRT risk < 30%, corresponding to scores < 68 points), intermediate-risk (PRT risk 30–70%, corresponding to scores 68–76 points), and high-risk (PRT risk > 70%, corresponding to scores > 76 points). In the training set, the actual transfusion rates were 13.0%, 45.4%, and 91.6% in the low-risk, intermediate-risk, and high-risk groups (Fig. 5).

Discussion

In the present study, we developed and validated a clinical prediction model for PRT risk using preoperative variables from 19,155 children undergoing cardiac surgery with CPB. The model incorporates eight variables and was subsequently used to classify patients into low-, intermediate-, and high-risk categories based on the predicted values derived from the nomogram. This stratification contributes to a more scientific approach to PRT management. To the best of our knowledge, this is the first study to construct a nomogram for PRT risk using preoperative variables from a large cohort of pediatric patients undergoing cardiac surgery with CPB. This model provides an effective tool for assessing transfusion risk in high-risk groups prior to surgery.

In cases of perioperative blood loss, RBC transfusion serves as a critical and potentially life-saving intervention. However, integrating it with a comprehensive blood conservation strategy may yield greater benefits [8]. Amid increasing surgical volumes and a global shortage of blood resources, recent studies have highlighted an

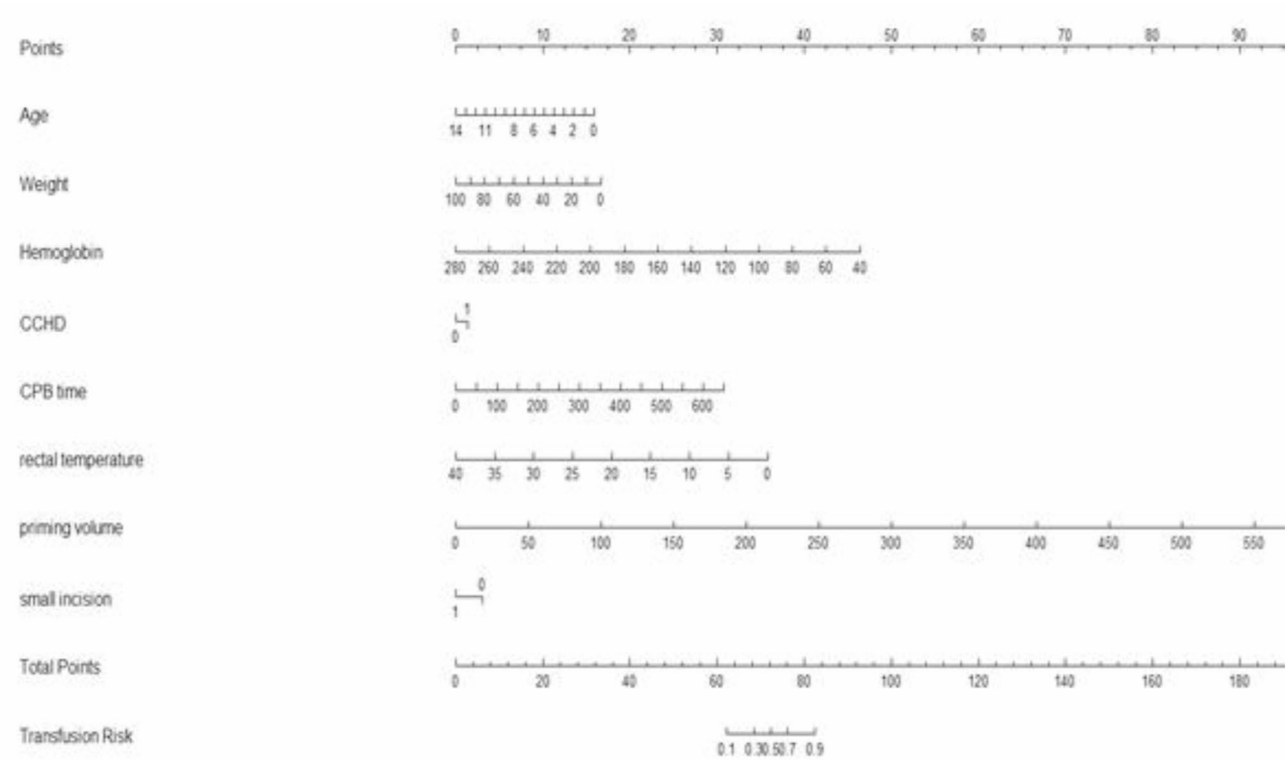

Fig. 3 Nomogram for the preoperative prediction of perioperative red blood cell transfusion (PRT) in children undergoing cardiac surgery with cardiopulmonary bypass (CPB). CCHD, cyanotic congenital heart disease; CPB, cardiopulmonary bypass; PRT, perioperative red blood cell transfusion; STAT, Society of Thoracic Surgeons-European Association for Cardio-Thoracic Surgery

association between RBC transfusion and a higher incidence of adverse events and mortality in pediatric cardiac surgery patients [9]. Therefore, clinicians are encouraged to carefully weigh the benefits against the risks before proceeding with RBC transfusions [10]. Advocacy from patient rights organizations further underscores the importance of avoiding transfusions that do not provide significant clinical benefits, aiming to minimize potential harm [11]. As a result, the evolving discipline of patient blood management (PBM) has embraced the concept of blood conservation as a cornerstone of perioperative care for children undergoing cardiac surgery. PBM is an evidence-based, multidisciplinary treatment strategy designed to maintain Hb levels, optimize hemostasis, minimize blood loss, and improve patient outcomes. It has been endorsed and recommended by leading organizations, including the World Health Organization, the American Society of Anesthesiologists, the European Society of Anesthesiology, and the Australian National Blood Authority [12–15]. Specific PBM guidelines for pediatric cardiac surgery emphasize perioperative blood conservation strategies [16, 17], which include identifying high-risk patients for RBC transfusion prior to surgery and implementing all available preoperative and intraoperative blood protection measures for this group. The assessment of PRT risk enables perfusionists to identify high-risk patients before surgery, facilitating the appropriate application of transfusion criteria and other blood conservation techniques, such as ultrafiltration, cell salvage, and miniaturized pediatric CPB systems. This approach enhances the efficiency of PRT management. Implementing this model could help alleviate the current challenges of blood resource shortages and improve clinical outcomes for patients. CPB is a critical component of pediatric cardiac surgery, and the use of CPB significantly influences PRT risk. To provide more targeted clinical guidance for pediatric CPB departments, patients undergoing off-pump cardiac surgery were excluded from this study. For patients identified as having a moderate or high risk of transfusion preoperatively, perfusionists must recognize and address these risks early, ensuring thorough preparation for necessary blood conservation measures during surgery. By adopting these comprehensive blood protection strategies, we aim to enhance the quality management practices of perfusionists and optimize patient care.

This scoring system is designed to enable clinicians to stratify patients into distinct risk groups based on quantified risks rather than relying solely on clinical experience prior to surgery. By doing so, clinicians can tailor specific indicators for targeted patients, thereby optimizing individualized care. It facilitates the reduction of unnecessary

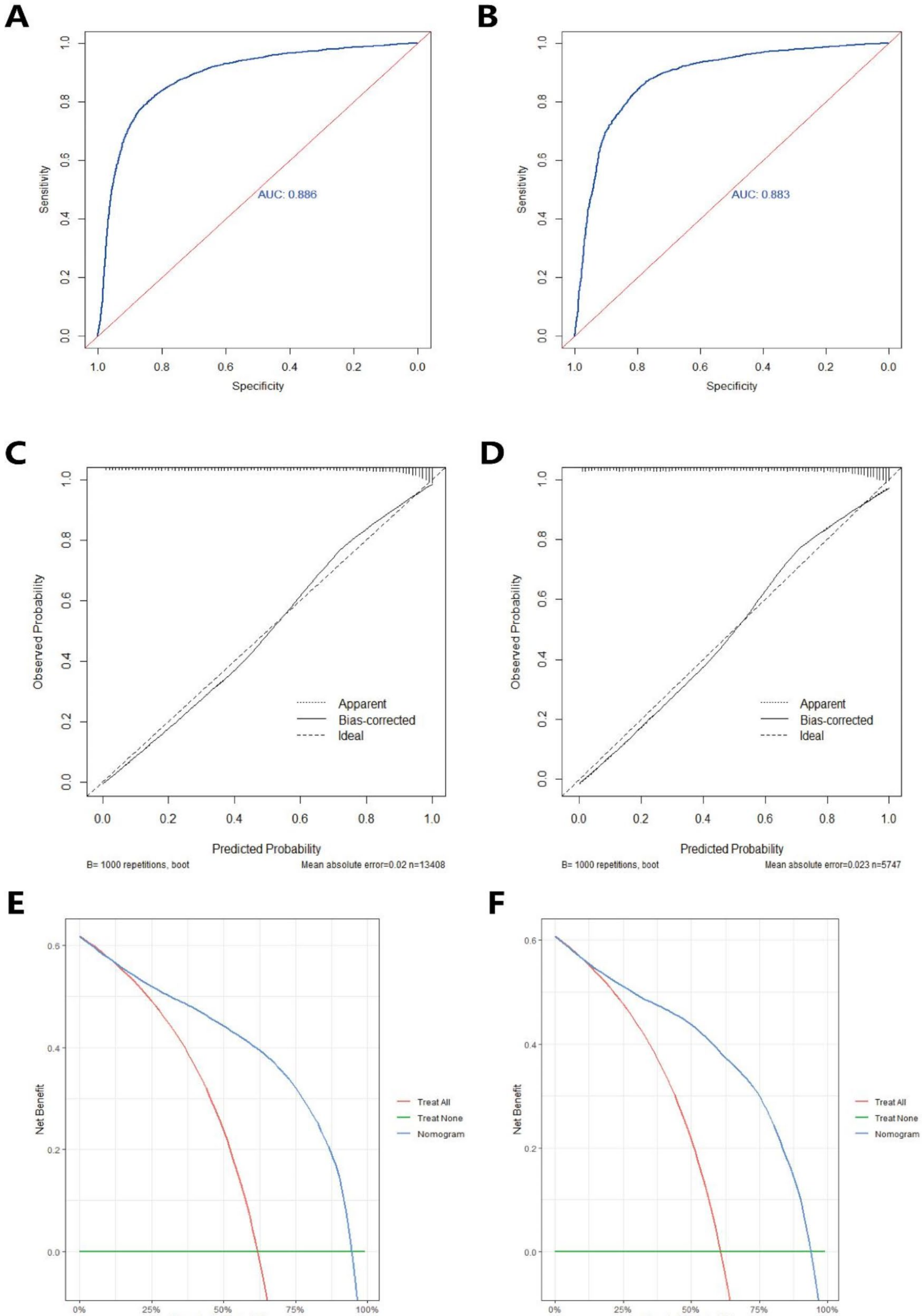

Fig. 4 Validation of the nomogram in the training and testing cohorts. (**A**, **B**) Receiver operating characteristic (ROC) curves. (**C**, **D**) Calibration curves. (**E**, **F**) Decision curve analysis (DCA) curves. AUC, area under the ROC curve

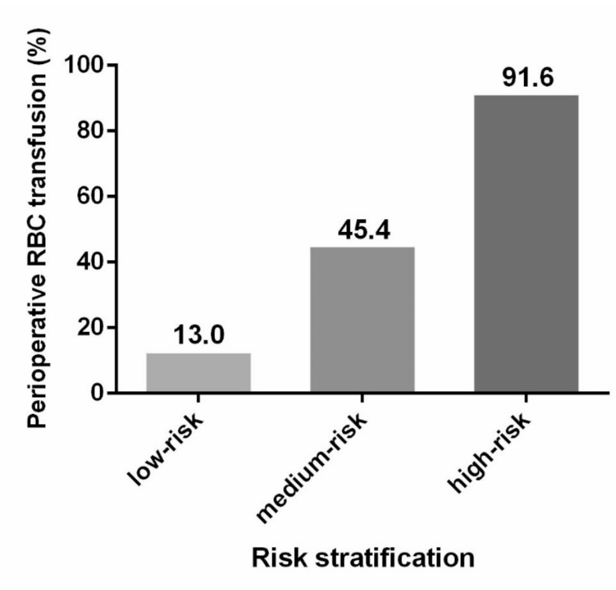

Fig. 5 The probability of actual perioperative red blood cell transfusion (PRT) in the training set across three risk groups

blood use in low-risk patients while encouraging the implementation of more proactive blood conservation strategies in medium- to high-risk populations. For this study, a wide range of surgical procedures were considered, including transposition of the great arteries, tetralogy of Fallot, pulmonary stenosis, and pulmonary atresia, among others. Our goal was to develop a predictive scoring system applicable to the majority of pediatric cardiac surgery patients undergoing CPB. When a pediatric patient presents with surgical indications, healthcare providers can utilize this tool to assess the risk of PRT and conduct a comprehensive evaluation. This approach equips clinicians with the information needed to make well-informed decisions regarding subsequent interventions, ultimately enhancing patient outcomes.

Over the years, numerous models have been developed to predict blood transfusion requirements in adult cardiac surgery patients [18]. However, predicting RBC transfusion needs in pediatric patients remains challenging due to the broader range of patient characteristics, smaller case volumes, and significant heterogeneity in diagnoses and managementstrategies. Moreover, the smaller total blood volume in children complicates efforts to achieve bloodless priming during CPB, making pediatric CPB surgery more dependent on allogeneic RBC transfusions compared to adult surgery [19]. Conducting comparative studies in pediatric cardiac surgery patients is inherently more difficult than in adults. To date, no clinical predictive model for PRT in pediatric cardiac surgery patients exists to guide clinicians in perioperative blood management. High-quality research in this area requires larger sample sizes and more comprehensive data. As the largest heart disease diagnosis and treatment center globally, our institution performs a high annual volume of pediatric cardiac surgeries, providing an extensive and robust dataset for this study. This large sample size has enabled us to develop a predictive model tailored to the unique needs of pediatric cardiac surgery patients.

Our study demonstrates that pediatric patients with younger age, lower weight, lower preoperative Hb levels, lower minimum rectal temperature during CPB, longer CPB duration, higher CPB priming volume, and those undergoing median sternotomy or diagnosed with CCHD are at a significantly higher risk of PRT. These findings align with results reported in other studies, further validating the identified risk factors. For instance, Williams et al. [20] analyzed 414 pediatric cases undergoing heart operation and observed an inverse relationship between age and both blood loss and transfusion requirements. Similarly, research by Miller et al. [21] involving 76 pediatric cases undergoing CPB surgery, noted increased bleeding in children weighing less than 8 kg compared to those weighing more than 8 kg. Moreover, Savan et al. [22] analyzed 182 pediatric cases undergoing heart operation with CPB, identifying a significant correlation between preoperative weight, CCHD, and postoperative bleeding. Children with CCHD are associated with hemorrhagic disorders and abnormal hemostasis [23, 24]. In a state of low coagulation, the primary mechanism is impaired fibrinogen function, as assessed by thromboelastography (TEG) functional fibrinogen assay [25]. A study by Yin et al. [26], which included 1,550 children undergoing congenital heart disease surgery with CPB, identified age, weight, and preoperative Hb levels as independent risk factors for intraoperative RBC transfusion. Frelinger et al. [27] demonstrated that hypothermia can impair platelet function, and the duration of CPB is associated with the downregulation of platelet count and function. The underlying mechanism may involve hypothermia inhibiting platelet aggregation, promoting the formation of adenosine diphosphate-induced leukocyte-platelet aggregates, attenuating the reduction in leukocyte-platelet aggregates induced by glycoprotein IIIa/IIb inhibitors, and reducing platelet factor activity. These effects collectively contribute to increased bleeding and a higher likelihood of transfusion. Besides, Mulaj et al., in a study of 334 pediatric patients undergoing CPB cardiac surgery, found that age (< 18 months), CPB priming volume (> 43 mL/kg), minimum rectal temperature during CPB (< 32℃), and preoperative hematocrit (< 34%) were independently associated with RBC transfusion [28]. These findings underscore the importance of thoroughly understanding and evaluating a patient's clinical characteristics prior to surgery to optimize perioperative management and minimize transfusion requirements.

This study has several limitations that should be acknowledged. First, our predictive model was developed and internally validated at a single institution, which may limit the generalizability of our findings. However, the study incorporated a wide range of surgical types and a substantial sample size, lending a degree of representativeness to the results. External validation at other centers will be necessary to further evaluate the model's performance in future studies. Second, due to the retrospective nature of this study, the absence of certain data may have excluded potential confounders, which could influence the accuracy of the model. Third, the 7-year study period may introduce time-related effects or other unknown changes not captured in the database, representing a potential source of bias. Besides, we did not report the quantity of RBC units transfused, and our model cannot distinguish between patients expected to receive one unit versus multiple units. Developing a model to predict the number of RBC units required represents a direction for future research. Finally, while most variables included in the tool can be determined preoperatively, certain factors, such as cardiopulmonary bypass duration and minimum rectal temperature, may not align with the surgical plan. This represents a limitation to the tool's utility during the operation.

Overall, we established and validated an effective clinical prediction model for PRT risk, incorporating risk stratification. The model utilizes eight variables to predict PRT risk in pediatric cardiac surgery patients undergoing CPB. Our nomogram, based on preoperative predictors, provides clinicians with a practical tool to assess PRT risk early and categorize patients into low-, intermediate-, or high-risk groups prior to surgery. This tool offers valuable guidance for clinical decision-making regarding PRT, including the implementation of blood conservation strategies for intermediate- to high-risk patients, and supports personalized evaluation of transfusion practices in clinical settings.

Glossary

PRT	Perioperative red blood cell transfusion
CPB	Cardiopulmonary bypass
DCA	Decision curve analysis
IQR	Inter-quartile range
IRB	Institutional Review Board
LASSO	Least absolute shrinkage and selection operator
RBC	Red blood cell
Hb	Hemoglobin
Hct	Hematocrit
PICU	Pediatric intensive care unit
AKI	Acute kidney injury
STAT	The Society of Thoracic Surgeons-European Association for Cardio-Thoracic Surgery
ROC-AUC	Area under the receiver operating characteristic curve
OR	Odds ratio
CI	Confidence interval
SD	Standard deviation
SE	Standard error

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12871-025-02917-2.

Supplementary Material 1

Author contributions

Jinping Liu: Conceptualization, Methodology, Software. Wenting Wang: Data curation, Wring-Original draft preparation, Software, Validation. He Wang: Data curation. Jia Liu: Visualization. Yu Jin: Wring-Reviewing and Editing. Bingyang Ji: Wring-Reviewing and Editing. All authors reviewed this manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethical approval

This work was approved by the ethical committee of Fuwai Hospital of the Chinese Academy of Medical Sciences (Beijing, China) (NO.2023–2265). Written informed consent was waived due to the retrospective nature of the study.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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