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RESEARCH

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Development and validation of a nomogram to pediatric postoperative pulmonary complications following thoracic surgery

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Abstract

Background Since the respiratory anatomy and physiology of children differ from those of adults, they are more susceptible to postoperative pulmonary complications after thoracic surgery that requires one-lung ventilation. Hypothesizing that the incidence of postoperative pulmonary complications could be predicted using easily accessible perioperative variables, we aimed to develop a nomogram specifically for children receiving thoracic surgery with one-lung ventilation.

Methods A total of 361 children undergoing thoracic surgery with one-lung ventilation were randomly assigned to two groups: a training cohort (80%) and a validation cohort (20%). The training cohort was utilized to develop a nomogram, whereas the validation cohort was used to assess its performance. The outcome of this study was the incidence of postoperative pulmonary complications. Univariate analysis and the least absolute shrinkage and selection operator regression model were applied to select the most relevant prognostic predictors. Multivariable logistic regression was used to develop a nomogram based on the selected prediction factors. Internal validation was conducted to evaluate its performance. The C-index and calibration plots were used to assess its discriminative ability and calibration.

Results Among the included patients, 109 (30.2%) presented postoperative pulmonary complications. Four predictive factors were ultimately selected to develop the nomogram. They were preoperative neutrophil-to-lymphocyte ratio, intraoperative ventilation mode, maximum peak airway pressure and minimum oxygenation index during one-lung ventilation. By incorporating these factors, the nomogram demonstrated strong C-indices of 0.909 (95% confidence interval (CI) [0.809–0.82]) and 0.871 (95% CI [0.795–0.945]) in the training and validation cohorts, respectively, along with well-matched calibration curves.

Conclusion The nomogram, based on four objective and easily assessed factors, demonstrates excellent predictive performance for pediatric postoperative pulmonary complications after one-lung ventilation, enabling early risk assessment and targeted interventions to improve patient outcomes.

Trial registration This study is registered at the Chinese Clinical Trial Registry (Registration number: ChiCTR2300072042, Date of Registration: 1/6/2023).

Keywords Nomogram, Children, One-lung ventilation, Postoperative pulmonary complications, PPCs, Thoracic surgery

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Introduction

Recently, significant progress has been made in comprehending the anatomical structure of children's airways, developing newer devices tailored for pediatric one-lung ventilation (OLV), and introducing innovative approaches to extraluminal bronchial blocker placement. These advancements have greatly contributed to the expanded use of OLV in pediatric surgery [1]. These characteristics may potentially contribute to the occurrence of postoperative pulmonary complications (PPCs), significantly affecting the patient's prognosis. In thoracic surgery, the incidence of PPCs is higher (19–59%) than in other types of major surgery not requiring OLV [2]. Several studies have affirmed that PPCs heighten morbidity and mortality rates while extending hospital stays during the perioperative period [3–6]. Therefore, identifying patients at risk is an important first step in improving clinical outcomes.

Concurrent with the growing availability of large data sets, a broad array of predictive models has been developed to assess the postoperative prognosis of surgical patients. PPCs of thoracic surgery in adults have been extensively investigated, and several prediction models have been developed to predict the occurrence risk of PPCs [7–10]. Pediatric patients undergoing thoracic surgery with OLV have distinct physiological and pathophysiological characteristics compared to adults, which influence the risk of PPCs. Children have more compliant chest walls, smaller airways, and higher respiratory rates, which alter their ventilatory mechanics. Their immature respiratory and immune systems also make them more vulnerable to lung injury and inflammation [11, 12]. These unique features necessitate a distinct approach to managing PPC risk in pediatric thoracic surgery. Although several articles have mentioned the factors affecting PPCs after pediatric OLV [13–15], a systematic and effective prediction model has not yet been established in children, and specific predictive studies on PPCs after pediatric OLV have not been carried out.

The study aimed to identify risk factors for PPCs in children undergoing thoracic surgery requiring OLV to develop a nomogram to predict the occurrence risk of pediatric PPCs, which can be used as a reference for clinical practice.

Methods

Ethics

Ethical approval for this study was provided by the institutional ethics committee of Hunan Children's Hospital (approval number: HCHLL-2023-60). And it was registered in the Chinese Clinical Trial Registry (registration number: ChiCTR2300072042) on 1 June 2023. We used the transparent reporting of a multivariable prediction model for individual prognosis or diagnosis (TRIPOD) checklist when writing our report [16]. All experiments were conducted in accordance with the Declaration of Helsinki and relevant guidelines. Informed consent was obtained from all subjects and/or their legal guardians before enrolled.

Study population

From January 2019 to February 2023, 980 children who underwent thoracic surgery at our institution were enrolled and analyzed. The exclusion criteria were as follows: emergency surgery; age >18 years old; patients who did not applicate OLV; patients who underwent reoperations within one month; and patients whose relevant data were missing or incomplete.

Data extraction

According to clinical practice, scientific knowledge, published research, and the actual data that can be collected for a retrospective study, 31 demographic and clinical variables of children who underwent thoracic surgery requiring OLV were collected. General information included age, sex, prematurity, corrected age, American Society of Anesthesiologists (ASA) grade, height, weight, disease treated this time, respiratory infection in the last month, and other respiratory diseases. Laboratory examination data before the operation included white blood cells, neutrophil-to-lymphocyte ratio (NLR), and red blood cells. Information on the anesthesia and operation management encompassed the duration of the operation, anesthesia, OLV, postoperative mechanical ventilation, model and placement of bronchial blocker, side of OLV, method and site of the operation, intraoperative ventilation mode, maximum peak airway pressure (Ppeak) and minimum oxygenation index (OI) during OLV, intraoperative infusion volume and blood loss, whether blood was transfused during the operation and so on.

Outcome measure

The outcome of interest in this study was PPCs. According to the detailed definition of European Perioperative Clinical Outcome (EPCO) [17], PPCs include respiratory infection, respiratory failure, pleural effusion, atelectasis, pneumothorax, bronchospasm, and aspiration pneumonia (show in Supplementary Table 1). PPCs were considered when any of these complications were detected within 72 h after surgery. To ensure a thorough evaluation of the incidence of PPCs, we formed a research group consisting of three highly experienced doctors. The diagnosis of PPCs was made meticulously, relying on a comprehensive analysis of the children's medical data by this dedicated research group. This approach was taken to ensure a preferred and accurate assessment of the occurrence of postoperative pulmonary complications.

Statistical analysis

All statistical analyses were carried out using SPSS 22.0 software (Chicago, IL, USA) and R software (version 4.0.3; https://www.Rproject.org). Candidate predictors were categorized after being assessed based on clinical reference values, scientific knowledge, and published articles. For continuous variables that conform to the normal distribution, the t test was used for comparison, and for continuous variables that are not normally distributed, the nonparametric test was used. For categorical variables, the X^2 test was used. Univariate analysis and the least absolute shrinkage and selection operator (LASSO) binary logistic regression model were used to screen several potential PPCs predictors from 31 candidate variables.

The correlation between predictor variables and pediatric PPCs was analyzed using multivariate logistic regression models. The prognostic intensity was quantified as odds ratios (ORs) with a 95% confidence interval (CI). A nomogram based on binary logic analysis was established to calculate the total scores of the nomogram for each patient in the training cohort. The accuracy, specificity, precision, sensitivity, and concordance index (C-index) were calculated, and a receiver operating characteristic (ROC) curve was drawn using R software to assess the predictive value of the model. An area under the receiver operator characteristics (AUC) curve analysis was used to evaluate the ability of the model to distinguish patients with PPCs. In a well-calibrated model, predictions should align with the 45-degree diagonal, representing the ideal match between observed outcomes and predicted probabilities.

All tests were 2-sided, and *P*-value <0.05 was considered statistically significant.

Results

Patient characteristics

During the study period, 980 children underwent thoracic surgery in our institution. Among the cases, 22 patients underwent emergency surgery, 482 patients did not undergo OLV during surgery (*e.g.,* the Nuss procedure for pectus excavatum), 97 children's relevant data were missing or incomplete, and 11 patients underwent reoperations within one month. No patients were older than 18 years old. Hence, a total of 361 patients were ultimately included in this study (show in Fig. 1). Of the included patients, 109 suffered PPCs, with an incidence of 30.2%.

Independent risk factors for PPCs

A total of 31 candidate features were extracted from the demographic and clinical variables. Supplementary Table 2 provides an overview of the demographic and clinical characteristics of the children. The preoperative NLR (*P*<0.0001), type of operation (*P*=0.022), duration of OLV (*P*=0.003), maximum Ppeak during OLV (*P*<0.0001), minimum OI during OLV (*P*<0.0001), and intraoperative ventilation mode (*P*<0.0001) were associated with PPCs. There was no significant difference in

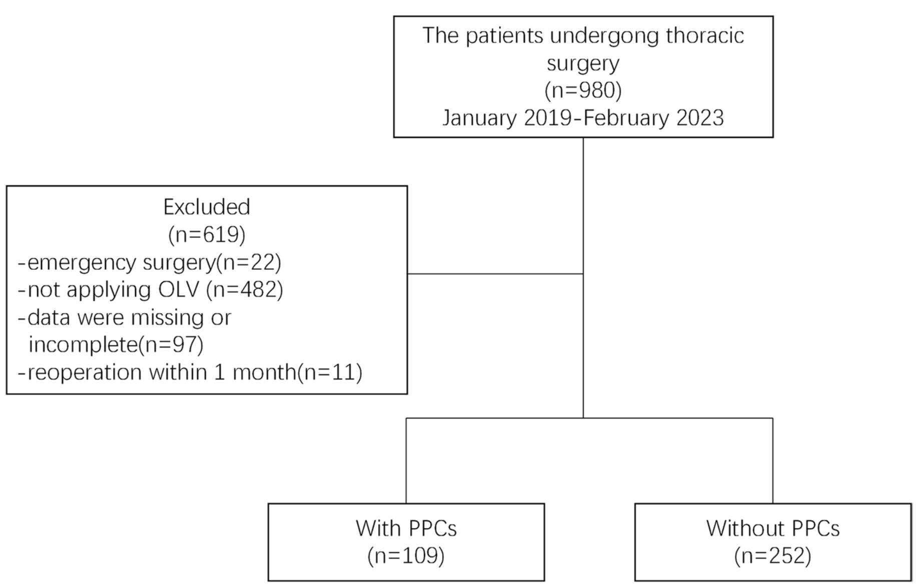

Fig. 1 Screening of the patient cohort for the development of the prediction model. OLV: one-lung ventilation; PPCs: postoperative pulmonary complications

the distributions of other characteristics between the two groups (with or without PPCs). The predictors selected by the LASSO logistic regression model had nonzero coefficients (show in Fig. 2).

Based on the univariate analysis and LASSO technique results, 4 final predictors were identified: preoperative NLR, maximum Ppeak during OLV, minimum OI during OLV, and intraoperative ventilation mode (shown in Table 1 and Fig. 3).

Table 1 Logistic regression analysis of clinical candidate predictors in the training set

Variable	OR (95%CI)	*p*-value
Preoperative NLR	2.237 (1.585–3.296)	<0.0001
Maximum Ppeak during OLV	1.231 (1.079–1.417)	0.002
Minimum OI during OLV	0.974 (0.959–0.987)	<0.0001
Intraoperative ventilation mode	0.223 (0.129–0.362)	<0.0001

• *OR* Odd ration, *CI* Confidence interval, *NLR* Neutrophil-to-lymphocyte ratio, *OLV* One-lung ventilation, *OI* Oxygenation index

Development and validation of a PPCs-predicting nomogram

The nomogram developed from the training cohort to predict PPCs for children undergoing thoracic surgery requiring OLV was shown in Fig. 4. The nomogram was created based on the following four factors: preoperative NLR, maximum Ppeak during OLV, minimum OI during OLV, and intraoperative ventilation mode. The total scores of the nomogram of each child in the training cohort were calculated. Table 2 provides information on the predictive performance of the nomogram, including accuracy, precision, sensitivity, specificity, and C-index. The AUC of the nomogram were 0.909 (95% CI, 0.872–0.945) in the training cohorts and 0.871(95% CI, 0.794–0.946) in validation cohorts (Fig 5). Since it was >0.75 and the Hosmer–Lemeshow test also produced a nonsignificant *p*-value of 0.1042, the nomogram was considered to have excellent discrimination [18]. In addition, the C-index was 0.909 (95% CI, 0.809–0.882) in the training cohorts and 0.871(95% CI, 0.795–0.945) in validation cohorts, which indicates the good performance of the nomogram in evaluating the risk of pediatric PPCs after OLV. The calibration plots with 100 bootstrap results of the nomogram are shown in Figure 6, which vividly demonstrates good agreement regarding the presence of PPCs between the risk estimation by the nomogram acquired from the training cohort and the actual PPCs occurrence in the training and validation cohorts.

Nomogram is simple and practical and can be widely applied in clinical practice, with high applicability

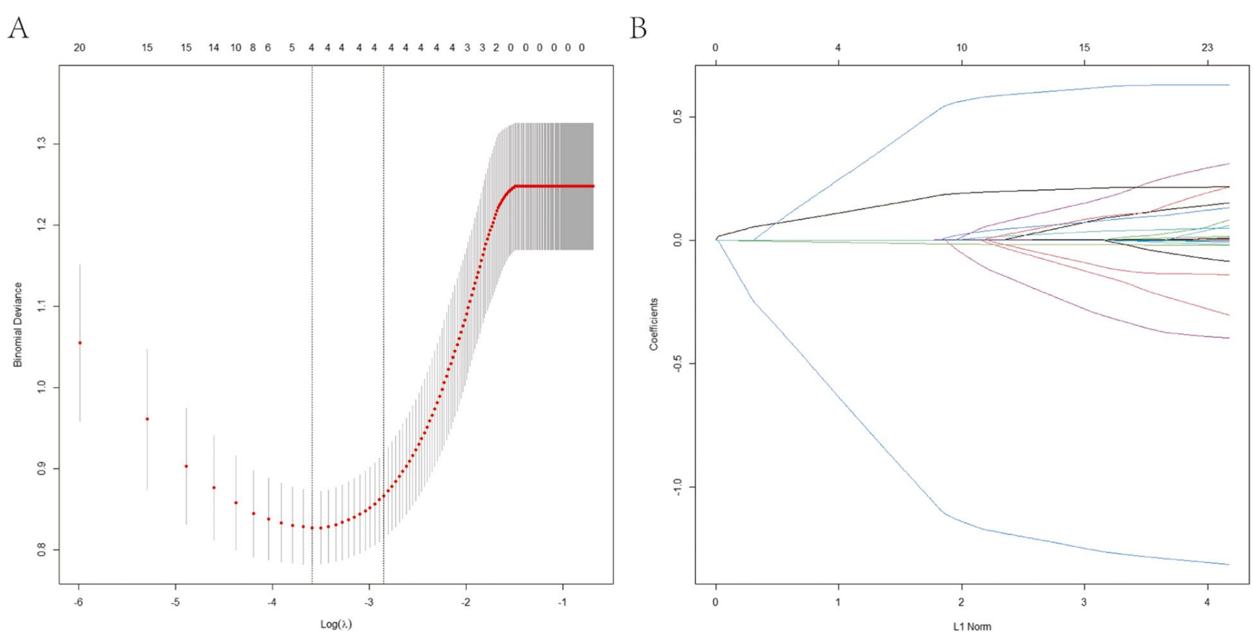

Fig. 2 Feature selection using the LASSO binary logistic regression model. **A** Tuning parameters (λ) selection in the LASSO model use 10-fold cross-validation via minimum criteria. The AUC curve was drawn against log (λ). Vertical lines were plotted at the optimal values using the minimum criteria and one standard error of the minimum criteria (the 1-SE criteria). A value of 0.063 with log (λ) of −1.20 was chosen (1-SE criteria) based on the 10-fold cross-validation. **B** The LASSO coefcient provides 36 texture features. A coefcient profle plot was plotted according to the log (λ) sequence. By using 10-fold cross-validation, the optimal λ generates 4 non-zero coefcients. LASSO: least absolute shrinkage and selection operator; AUC: area under the receiver operating characteristic

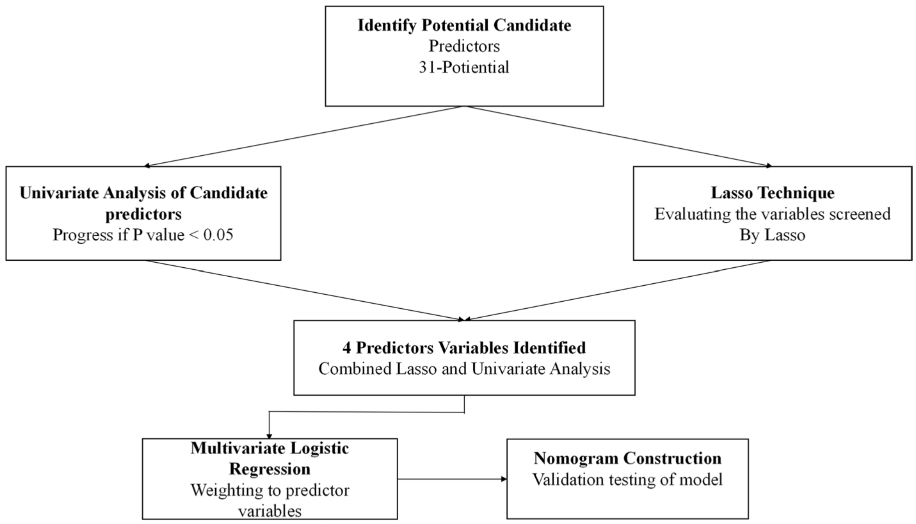

Fig. 3 The least absolute shrinkage and selection operator binary logistic regression model were applied for feature selection, while the univariate Analysis was used for potential predictor selection

[19–23]. When using the nomogram, each variable should be positioned on the corresponding axis to find the corresponding score, and the points of all variables are added to determine the risk. For example, a child undergoing thoracic surgery that required OLV had a preoperative NLR of 1 (5 points), and the ventilation mode applied during the surgery was PCV mode (20 points), the maximum Ppeak during OLV was 26 mmHg (30 points), and the minimum oxygenation index during OLV was 100 mmHg (90 points), resulting in a total score of 145. Therefore, the predicted risk of PPCs for this child was approximately 77% (show in Fig. 4).

Discussion

In the present study, a nomogram was developed and internally validated to predict the risk of PPCs in children undergoing thoracic surgery requiring OLV. The nomogram constructed in this study exhibited good performance in both predictive model development and internal validation. The incidence of pediatric PPCs could most reliably be predicted by the model including preoperative NLR, maximum Ppeak during OLV, minimum OI during OLV, and intraoperative ventilation mode. These indicators are easily obtainable in clinical practice, rendering the predictive model easy to extend and apply. Therefore, this nomogram is recommended for clinical practice in the pediatric population.

The observed incidence of PPCs in this study was 30.2%. It was similar to those found in some previous articles [24, 25], but higher than those in other studies [13, 26] The variation across studies may be attributed to the broad definition of PPCs in the guidelines (*e.g.,* pure pleural effusion not requiring treatment is also considered as PPCs). In addition, among the published studies related to PPCs during OLV, the majority of the study population are adults. However, considering the respiratory physiological characteristics of children[1], they are prone to PPCs when undergoing OLV [11, 13].

OI is utilized to assess pulmonary function and oxygenation status, providing valuable information on the severity of lung disease and predicting outcomes following lung injury. Due to its important guiding significance in OLV, the OI is commonly employed as an indicator of lung injury severity in children [27]. When children undergo thoracic surgery that requires OLV, the lower OI during OLV reflects a more severe intrapulmonary shunt and poorer lung function, making them more prone to lung injury and PPCs.

In addition to minimum OI during OLV, the ventilation mode applied was a strong predictor associated with the occurrence of PPCs. Consistent with some articles comparing the use of three ventilation modes in adults [28–30], we also found in the present study that the incidence of PPCs in children using the pressure control ventilation-volume guaranteed (PCV-VG) mode was significantly lower than that of the other two ventilation modes. Therefore, we suggest using the PCV-VG mode that combines the advantages of the other two modes in children with OLV to reduce the incidence of PPCs.

The NLR reflects the balance of neutrophils and lymphocytes in the body and is more accurate and stable than neutrophils and lymphocytes [31]. In recent years, it has been considered an important inflammatory response marker for diagnosing and evaluating patient prognosis [32–35]. In

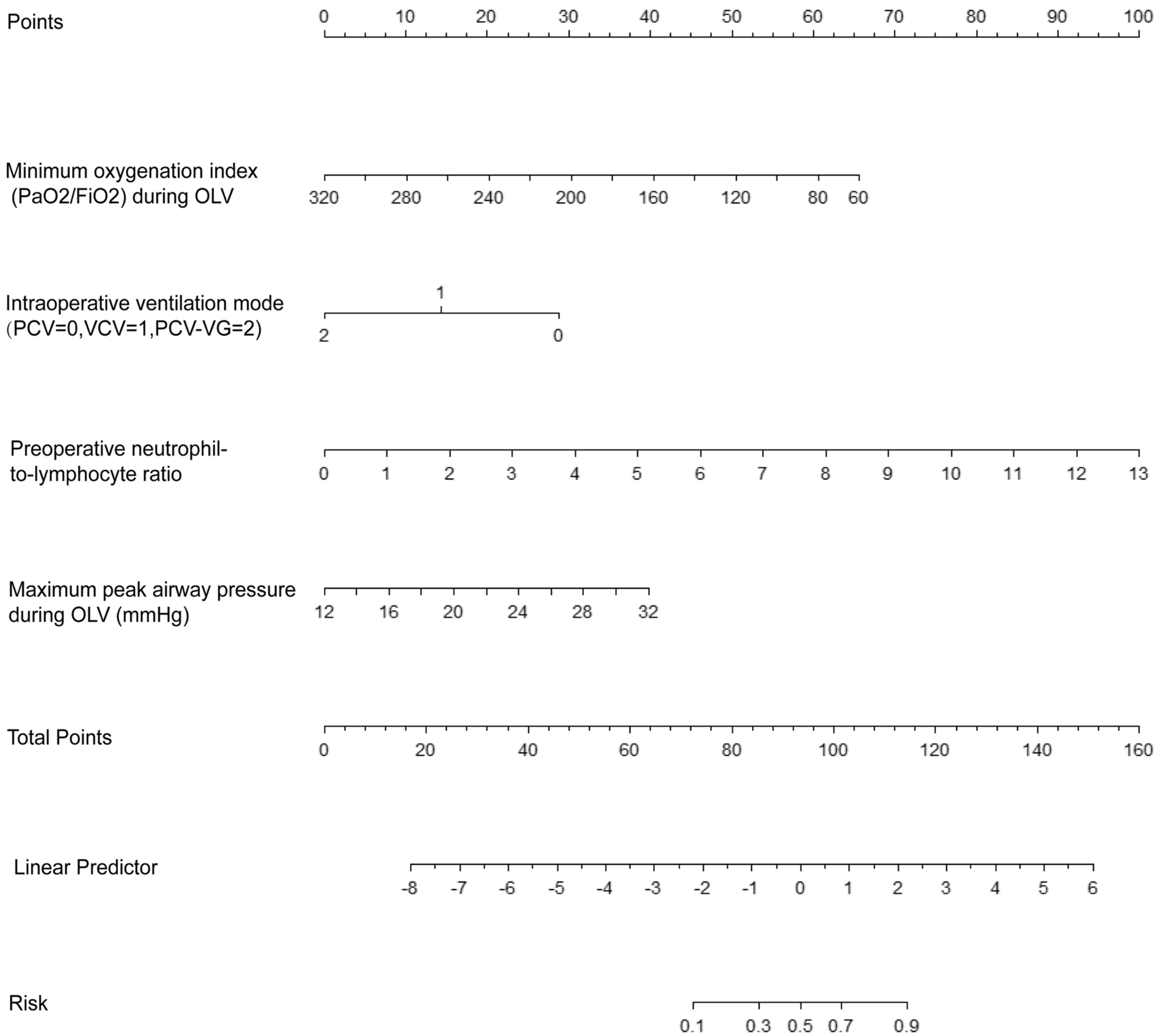

Fig. 4 The nomogram developed for the prediction of PPCs in children undergoing thoracic surgery requiring OLV. OLV: one-lung ventilation; PPCs: postoperative pulmonary complications; PCV: pressure-controlled ventilation; VCV: volume-controlled ventilation; PCV-VG: pressure-controlled ventilation - volume guaranteed

Table 2 Prediction performance of the nomogram

	Training cohort (*n*=289)	**Testing cohort (*n*=72)**
Cut-off points	0.422	0.266
Accuracy	0.873	0.842
Precision	0.826	0.879
Sensitivity	0.765	0.912
Specificity	0.923	0.642
AUC of the nomogram (95% CI)	0.909 (0.872–0.945)	0.871 (0.794–0.946)
C-index of the nomogram (95% CI)	0.909 (0.809–0.882)	0.871 (0.795–0.945)

PPCs Postoperative pulmonary complication, *AUC* Area under the receiver operating characteristic curve, *CI* Confidence interval

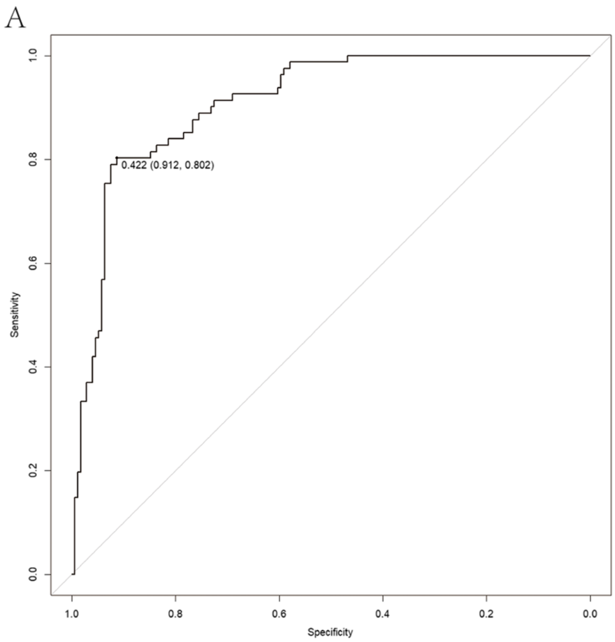

Fig. 5 AUCs of the nomogram used to predict PPCs following thoracoscopic surgery in the training and validation cohorts. **A** AUC in the training cohorts: 0.909 (95% CI, 0.872–0.945); **B** AUC in the validation cohorts: 0.871(95% CI, 0.794–0.946). AUC: area under the receiver operating characteristic; PPCs: postoperative pulmonary complications; OLV: one-lung ventilation

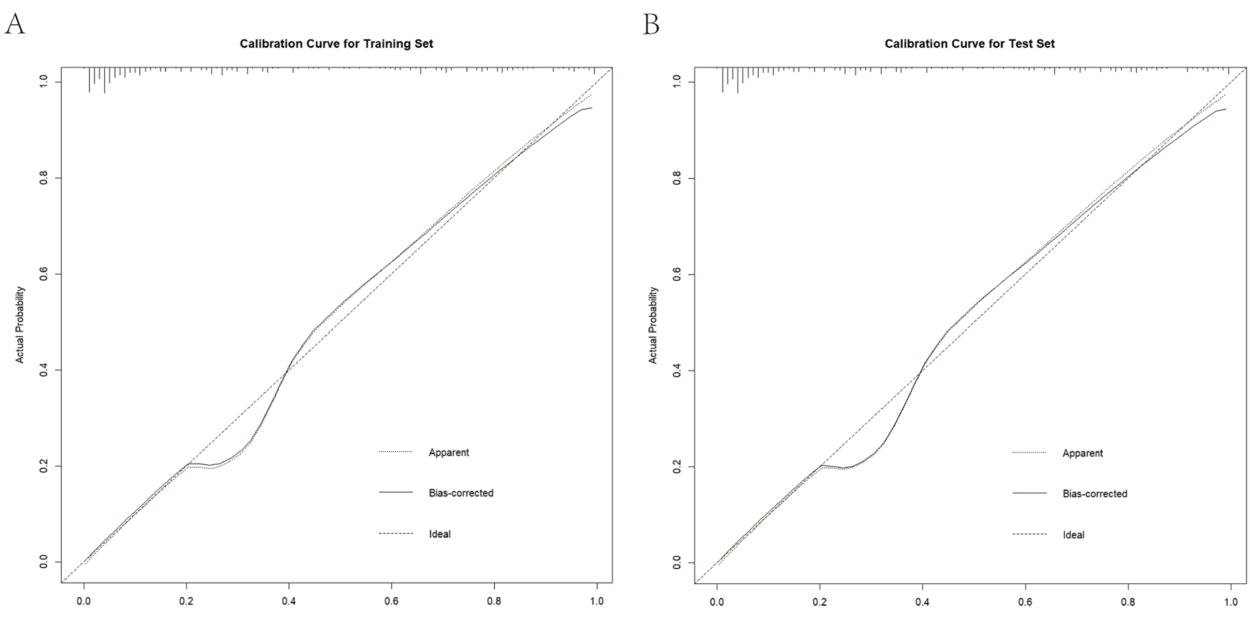

Fig. 6 Calibration curves of the nomogram. **A** the training cohorts, **B** the validation cohorts. Illustration of the agreement between the predicted risk of pediatric PPCs and the observed outcomes of PPCs in children undergoing thoracic surgery requiring OLV. PPCs: postoperative pulmonary complications; OLV: one-lung ventilation

this study, we found that the NLR within 48 hours before surgery is also an important predictor of PPCs in children undergoing thoracic surgery requiring OLV, which is consistent with previous reports [36, 37].

Ppeak reflects the dynamic compliance of the respiratory system, affected by inspiratory flow and tracheal catheter diameter, which is the main source of resistance during mechanical ventilation [38, 39]. With the initiation of OLV in the lateral decubitus position, the dependent lung solely ventilates and is accompanied by gravitational compression of the mediastinum. Meanwhile, the nondependent lung collapses, leading to atelectasis and decreased compliance. Therefore, elevated Ppeak during OLV is commonly encountered. However, a higher Ppeak will not only affect ventilation/perfusion matching, leading to significant hypoxemia during OLV, but may also cause pulmonary barotrauma, thus increasing the incidence of PPCs [1, 38, 40, 41].

The study has some notable strengths. First, it established a prediction model for PPCs in the pediatric population for the first time. Second, the data for model development were derived from one of the largest children's hospitals in China and the sole tertiary referral pediatric hospital in Hunan Province, which could potentially reduce the impact of geographic and demographic variability. However, several limitations need to be considered. Firstly, this study was retrospective; therefore, some variables that may have an impact on PPCs were not included due to missing records. Secondly, although this study used random data splitting to maximize model accuracy and applicability, external validation was not performed. Future research should focus on multicenter validation to assess the model's generalizability across different settings. Lastly, this study was limited to evaluating the incidence of PPCs within the first 72 hours after surgery and did not examine their occurrence beyond this early postoperative period. This limitation underscores the need for future research to investigate late-onset pulmonary complications, in order to achieve a more comprehensive understanding of long-term postoperative risks.

Conclusion

This study has identified four straightforward and easily assessable factors related to the emergence of PPCs. A nomogram was constructed by integrating these risk factors for pediatric PPCs. The model provides a good estimation of PPCs risk in children undergoing thoracic surgery that required OLV, which may have the potential for timely intervention.

Abbreviations

PPCs	Postoperative pulmonary complications
OLV	One-lung ventilation
OR	Odds ratios
CI	Confidence interval
ASA	American Society of Anesthesiologists
NLR	Neutrophil-to-lymphocyte ratio
Ppeak	Peak airway pressure
OI	Oxygenation index
EPCO	European Perioperative Clinical Outcome
LASSO	The least absolute shrinkage and selection operator
C-index	Concordance index
ROC	Receiver operating characteristic
AUC	Area under the receiver operator characteristics
PCV-VG	Pressure control ventilation-volume guaranteed
VGV	Volume-controlled ventilation
PCV	Pressure-controlled ventilation

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12871-025-03122-x.

Supplementary Material 1.

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Authors' contributions

LW: Conceptualization; Data curation; Formal analysis; Methodology; Writing - original draft. TX: Funding acquisition; Project administration. ZD: Supervision; Resources. TGC: Software; Validation; Writing - review & editing. DJP: Data curation; Methodology. SQQ: Funding acquisition; Project administration; Writing - review & editing. All authors read and approved the final submitted version.

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Data availability

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

Declarations

Ethics approval and consent to participate

Ethical approval for this study was provided by the institutional ethics committee of Hunan Children's Hospital (approval number: HCHLL-2023-60). And it was registered in the Chinese Clinical Trial Registry (registration number: ChiCTR2300072042) on 1 June 2023. All experiments were conducted in accordance with the Declaration of Helsinki and relevant guidelines. Informed consent was obtained from all subjects and/or their legal guardians before enrolled. All authors listed meet the authorship criteria according to the latest guidelines of the International Committee of Medical Journal Editors, and that all authors are in agreement with the manuscript. Written informed consent was taken from all the patients.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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