Research Article

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Risk Factors for Postoperative Pulmonary Complications Following Posterior Spinal Fusion in Adolescent Scoliosis: A Retrospective Cohort Study

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ABSTRACT

Objective Scoliosis is a prevalent spinal deformity that severely impacts the physical and psychological well-being of adolescents and often requires surgical correction. This study aimed to investigate the risk factors for postoperative pulmonary complications (PPCs) following posterior spinal fusion in adolescent scoliosis, with a specific focus on evaluating the predictive value of preoperative forced vital capacity (FVC) and etiological classification.

Methods This retrospective cohort study enrolled adolescents who underwent posterior spinal fusion for scoliosis correction at Peking Union Medical College Hospital between January 2018 and December 2022. The baseline demographic, clinical, and perioperative variables were collected. The primary endpoint was the occurrence of PPCs prior to hospital discharge. Univariate and multivariable binary logistic regression analyses were conducted to identify independent risk factors.

Results A total of 1,234 patients were included, of whom 29 (2.35%) developed PPCs and 1,205 did not. Univariate analysis revealed that 12 variables, including non-idiopathic scoliosis, a larger main thoracic curve, a decreased FVC% predicted, and increased perioperative blood transfusions, were significantly associated with PPCs ($P < 0.05$). Multivariable logistic regression model showed that non-idiopathic scoliosis emerged as the sole independent risk factor for PPCs [adjusted odds ratio (OR) = 5.478, 95% confidence interval: 2.017–19.148, $P = 0.002$]. Preoperative FVC% predicted (adjusted $OR = 0.993$, $P = 0.497$) and main thoracic curve (adjusted $OR = 1.002$, $P = 0.736$) did not demonstrate independent predictive value.

Conclusions Non-idiopathic scoliosis, rather than preoperative pulmonary function or curve severity, is an independent risk factor for PPCs following posterior spinal fusion in adolescents. During perioperative respiratory risk assessment, particular emphasis should be placed on the etiological classification of these patients.

Key words: scoliosis; adolescent; spinal fusion; postoperative complications; respiratory function tests; risk factors

INTRODUCTION

Adolescent scoliosis is a prevalent spinal deformity that severely impacts the physical and psychological well-being of adolescents[1]. It primarily encompasses adolescent idiopathic scoliosis (AIS) and non-idiopathic scoliosis[2]. For patients with rapidly progressive curves, posterior spinal fusion (PSF) remains the standard surgical intervention[3, 4]. However, patients requiring sur-

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gery often present with compromised baseline pulmonary function[5]. Combined with extensive surgical trauma, substantial intraoperative blood loss, and prolonged operative time, postoperative pulmonary complications (PPCs) including pneumothorax, pleural effusion, pneumonia, and even respiratory failure frequently occur[6, 7]. PPCs not only prolong hospital length of stay and increase healthcare costs but also can be life-threatening in severe cases[8].

Identifying the risk factors for PPCs in patients with adolescent scoliosis has long been a research focus, yet the conclusions remain controversial[9, 10]. Preoperative pulmonary function tests (PFTs), particularly forced vital capacity (FVC) and its percentage of the predicted value (FVC% predicted), are conventionally regarded as core indicators for assessing surgical tolerance[11, 12]. The traditional perspective holds that a decreased FVC% is associated with PPCs. Recently, however, some scholars have pointed out that a decline in FVC% is often highly correlated with the severity of the spinal deformity (e.g., Cobb angle) or specific underlying etiologies (e.g., neuromuscular diseases)[13, 14]. Whether FVC% itself constitutes an independent risk factor requires further validation. Furthermore, previous studies have predominantly focused on single disease entities, such as idiopathic scoliosis or congenital scoliosis with relatively small sample sizes, lacking comprehensive analyses involving different etiological classifications within a large-scale cohort.

To address this gap, this study retrospectively analyzed the clinical data of 1,234 adolescent patients with scoliosis who underwent posterior correction and spinal fusion at our institution. By employing a large-sample univariate and multivariable regression analysis, we aimed to explore the true risk factors for the development of PPCs. Specifically, we sought to clarify the relative weights of etiological classification and preoperative pulmonary function in predicting the risk of complications, thereby providing evidence-based guidance for perioperative risk assessment and management strategies.

PATIENTS AND METHODS

Study design and patient population

This was a single-center, retrospective cohort study. We reviewed the electronic medical records of adolescent patients who underwent PSF for scoliosis at Peking Union Medical College Hospital between January 2018 and December 2022. The study protocol was approved by the Institutional Review Board of Peking Union Medical College Hospital (I-26PJ0464). Verbal informed consent was obtained by telephone from patients or their legal guardians whenever feasible; for those who could not be contacted, the requirement for informed consent was waived.

The inclusion criteria were: (1) age between 10 and 18 years; (2) confirmed diagnosis of scoliosis including both AIS and non-idiopathic etiologies; (3) undergoing primary posterior pedicle screw instrumentation and spinal fusion (including both primary and revision surgeries); and (4) availability of complete preoperative full-spine radiographs. The exclusion criteria were: (1) tumor-related spinal deformities: spinal destruction and deformity caused by primary spinal tumors (e.g., osteosarcoma, giant cell tumor of bone) or metastatic tumors; (2) non-fusion spinal surgeries (e.g., growth rod instrumentation); (3) non-posterior spinal surgeries (e.g., anterior or lateral approaches); (4) surgery without instrumentation (e.g., debridement only); (5) presence of acute upper respiratory tract infections or pneumonia within two weeks prior to surgery; (6) pre-existing chronic pulmonary diseases requiring continuous medical intervention (e.g., acute exacerbation of asthma); and (7) substantial missing data regarding critical baseline characteristics, which are defined as age, sex, scoliosis etiology, primary outcome, and key radiographic parameters.

Data collection

Clinical data were systematically extracted from the institutional electronic database. The collected variables included: (1) Demographics and clinical characteristics: age, sex, body mass index (BMI), and American Society of Anesthesiologists (ASA) physical status classification; (2) Scoliosis classification: patients were categorized into the AIS group and the non-AIS group (congenital, neuromuscular, and syndromic scoliosis, etc.) based on their primary etiology; (3) Radiographic parameters: preoperative main thoracic curve, lumbar curve, and thoracic kyphosis were measured on standing full-length spinal radiographs; (4) Preoperative pulmonary function: FVC and forced expiratory volume in one second (FEV_1), both expressed as a percentage of the predicted value (FVC% predicted and FEV_1% predicted); (5) Surgical and perioperative details: operative time, number of fused levels, estimated blood loss (EBL), and the volume of allogeneic red blood cell (RBC) and fresh frozen

plasma (FFP) transfused perioperatively.

Outcomes

The primary endpoint was the occurrence of PPCs prior to hospital discharge. PPCs were defined as any newly developed respiratory adverse event requiring specific medical intervention. These included: (1) symptomatic pneumothorax or pleural effusion requiring therapeutic thoracentesis or tube drainage; (2) atelectasis confirmed by chest radiographs with oxygen desaturation or clinical symptoms; (3) pneumonia diagnosed based on typical clinical manifestations combined with new infiltrates on imaging; (4) respiratory failure, characterized by hypoxemia (PaO_2 < 60 mmHg, 1 mmHg = 0.133 kPa) and/or hypercapnia ($PaCO_2$ > 50 mmHg) on arterial blood gas analysis; (5) delayed extubation, defined as the need for mechanical ventilation for > 24 hours postoperatively or the requirement for reintubation; and (6) airway obstruction confirmed by laryngoscopy or imaging.

Statistical analysis

All statistical analyses were performed using the R statistical software (version 4.3.2, The R Foundation for Statistical Computing, Vienna, Austria). For continuous variables, normally distributed data were presented as mean ± standard deviation and compared using independent Student's *t*-test, whereas non-normally distributed variables were expressed as median (interquartile range) and compared using Wilcoxon rank-sum test. Categorical variables were presented as frequencies and percentages (%), and compared using Pearson's Chi-square test or Fisher's exact test, as appropriate.

To identify the risk factors for PPCs, a univariate logistic regression analysis was initially performed to calculate crude odds ratios (*OR*s) and 95% confidence intervals (*CI*s) for each potential predictor. Variables that demonstrated statistical significance in the univariate analysis, along with those of established clinical importance were subsequently incorporated into a multivariable binary logistic regression model. To avoid multicollinearity and evaluate the independent effect of each variable after adjusting for confounders, the enter method was applied rather than stepwise selection.

Patients with substantial missing data regarding critical baseline characteristics were excluded according to the exclusion criteria. For variables with a missing rate of < 20% (including preoperative PFTs, EBL, and several baseline clinical parameters with minor missingness), multiple imputation was performed using chained equations (MICE) algorithm to generate five imputed datasets, utilizing complete covariates as auxiliary predictors[15]. All available baseline characteristics and outcome variables were included in the imputation model. To validate the missing at random (MAR) assumption, baseline characteristics and primary outcomes were compared between patients with complete and missing data. Multivariable logistic regression analysis was performed on each imputed dataset, and the results were pooled according to Rubin's rules to calculate final adjusted *OR*s and 95% *CI*s. Statistical significance was defined as a two-sided *P* value of < 0.05.

RESULTS

Patient population and baseline characteristics

A total of 2,196 patients who underwent scoliosis surgery were identified. According to the inclusion and exclusion criteria, 1,234 adolescent patients who underwent PSF for scoliosis were included. Among them, 29 patients developed PPCs prior to discharge, yielding an overall incidence rate of 2.35%. A total of 35 episodes of PPCs occurred in these 29 patients. The specific types of complications included pleural effusion (*n* = 20), pulmonary infection (*n* = 7), respiratory failure or delayed extubation (*n* = 5), pneumothorax (*n* = 2), and airway obstruction (*n* = 1). The overall study flowchart is presented in **Figure 1.**

Regarding data completeness, most key variables were well-documented with a missing rate of < 5%. Preoperative pulmonary function parameters (e.g., FVC% and FEV_1%) were missing in 214 (17.34%) cases, and records of EBL were missing in 140 (11.35%) cases. As detailed in the Methods section, these missing values were addressed using multiple imputation. A comparative analysis between patients with complete and missing preoperative pulmonary function data revealed no clinically significant differences in baseline covariates or the incidence of PPCs (Supplementary **Table S1**), indicating that the missing data were likely missing at random and the imputation did not introduce significant selection bias.

The baseline demographics, clinical characteristics, and perioperative variables of the non-PPCs group (*n* = 1,205) and the PPCs group (*n* = 29) are summarized in **Table 1**. There were no significant dif-

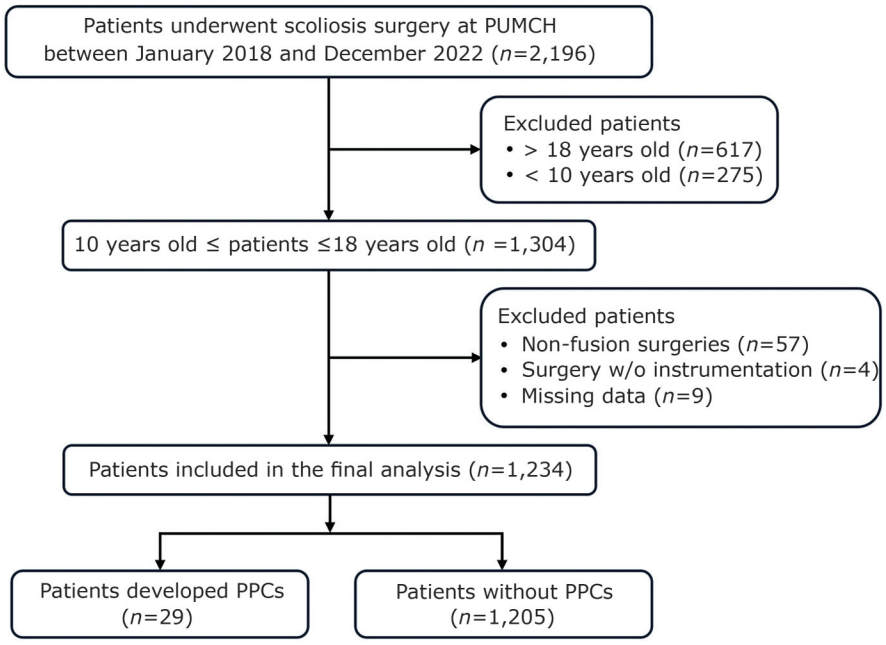

Figure 1. Overall study flowchart.
PUMCH: Peking Union Medical College Hospital; w/o: without; PPCs: postoperative pulmonary complications.

ferences between the two groups regarding sex, height, weight, BMI, or history of spinal surgery (P > 0.05). Compared with the non-PPCs group, patients in the PPCs group were significantly younger (12.90 ± 2.01 years vs. 13.95 ± 1.94 years, P = 0.004) and had a higher proportion of ASA physical status class Ⅲ – Ⅳ (13.8% vs. 4.1%, P = 0.034). Regarding the scoliosis etiology, the proportion of non-idiopathic scoliosis was significantly higher in the PPCs group than that in the non-PPCs group (86.2% vs. 45.6%, P < 0.001). A detailed breakdown of the non-AIS etiologies is also provided. Within the PPCs group, patients with congenital scoliosis constituted most of the non-AIS cases (n = 18, 62.0%), followed by other etiologies (n = 3, 10.3%), Marfan syndrome (n = 2, 6.9%), neuromuscular scoliosis (n = 1, 3.4%), and neurofibromatosis (n = 1, 3.4%). In terms of deformity severity, the PPCs group presented with a significantly larger preoperative main thoracic curve [54° (42°, 78°) vs. 48° (32°, 63°), P = 0.043] and greater thoracic kyphosis [36° (23°, 55°) vs. 26° (18°, 38°), P = 0.012] compared with the non-PPCs group. In terms of pulmonary function, the PPCs group had significantly lower FVC% predicted [75.0% (52.9%, 87.6%) vs. 84.0% (72.1%, 95.0%), P = 0.009] and FEV_1% predicted [74.0% (53.6%, 95.0%) vs. 85.9% (71.3%, 97.9%), P = 0.013]. During the perioperative period, the PPCs group required a longer operative time (281.34 ± 78.18 minutes vs. 240.70 ± 82.82 minutes, P = 0.009) and greater volumes of allogeneic RBC [2 (0, 2) U vs. 0 (0, 0) U, P < 0.001) and FFP [200 (0, 400) mL vs. 0 (0, 0) mL, P < 0.001) transfusions.

Table 1. Baseline characteristics and perioperative variables of patients with and without PPCs

Variables	Non-PPCs group (n = 1,205)	PPCs group (n = 29)	P value
Demographics			
Age (yrs, means ± SD)	13.95 ± 1.94	12.90 ± 2.01	0.004
Sex [n (%)]			0.183
Male	341 (28.3)	12 (41.4)	
Female	864 (71.7)	17 (58.6)	
Height (cm, means ± SD)	160.05 ± 10.61	156.93 ± 11.01	0.119
Weight (kg, means ± SD)	49.18 ± 12.47	47.21 ± 14.30	0.401
BMI (kg/m², means ± SD)	19.06 ± 3.79	18.89 ± 3.92	0.818
ASA classification [n (%)]			0.034

Table 1. Baseline characteristics and perioperative variables of patients with and without PPCs (continued)

Variables	Non-PPCs group (*n* = 1,205)	PPCs group (*n* = 29)	*P* value
Ⅰ–Ⅱ	1,155 (95.9)	25 (86.2)	
Ⅲ–Ⅳ	50 (4.1)	4 (13.8)	
Preoperative pulmonary function			
FEV_1 [% of predicted, median (IQR)]	85.9 (71.3, 97.9)	74.0 (53.6, 95.0)	0.013
FVC [% of predicted, median (IQR)]	84.0 (72.1, 95.0)	75.0 (52.9, 87.6)	0.009
FEV_1/FVC [median (IQR)]	86.4 (81.1, 91.0)	85.1 (80.7, 90.7)	0.461
Preoperative hematologic profile			
Preoperative anemia [*n* (%)]	51 (4.2)	0 (0)	0.692
Hemoglobin (g/L, means ± SD)	134.28 ± 13.54	138.55 ± 11.17	0.092
Albumin (g/L, means ± SD)	43.57 ± 3.15	43.21 ± 2.30	0.535
hsCRP (mg/L, means ± SD)	1.06 ± 3.77	0.73 ± 1.40	0.629
Preoperative scoliosis characteristics			
Scoliosis type [*n* (%)]			< 0.001
AIS	656 (54.4)	4 (13.8)	
Non-AIS	549 (45.6)	25 (86.2)	
Congenital scoliosis	268 (22.2)	18 (62.0)	-
Neuromuscular scoliosis	108 (9.0)	1 (3.4)	-
Neurofibromatosis	64 (5.3)	1 (3.4)	-
Marfan syndrome	41 (3.4)	2 (6.9)	-
Other etiologies*	68 (5.6)	3 (10.3)	-
History of spinal surgery [*n* (%)]	93 (7.7)	5 (17.2)	0.073
Main thoracic curve [°, median (IQR)]	48 (32, 63)	54 (42, 78)	0.043
Lumbar curve [°, median (IQR)]	26 (0, 45)	0 (0, 35)	0.039
Thoracic kyphosis [°, median (IQR)]	26 (18, 38)	36 (23, 55)	0.012
Surgical parameters			
Operation time (min, means ± SD)	240.70 ± 82.82	281.34 ± 78.18	0.009
Number of fused levels (*n*, means ± SD)	10.53 ± 3.32	11.28 ± 3.45	0.234
Fusion extending to thoracic spine [*n* (%)]	1,173 (97.3)	29 (100.0)	1.000
Postoperative thoracic curve [°, median (IQR)]	13 (5, 21)	15 (8, 31)	0.174
Postoperative lumbar curve [°, median (IQR)]	3 (0, 10)	0 (0, 3)	0.018
Postoperative thoracic kyphosis [°, median (IQR)]	23 (19, 30)	27 (19, 31)	0.609
Correction rate of main thoracic curve [%, median (IQR)]	65.79 (34.78, 77.08)	73.33 (59.26, 80.49)	0.038
Correction rate of lumbar curve [%, median (IQR)]	46.05 (0, 80.95)	0.00 (0, 64.86)	0.037
Correction rate of thoracic kyphosis [%, median (IQR)]	11.11 (–13.04, 34.48)	38.89 (6.67, 52.83)	0.001
Blood management			
Estimated blood loss (mL, median (IQR))	500 (300, 600)	500 (400, 800)	0.067
RBC transfused (U, median (IQR))	0 (0, 0)	2 (0, 2)	< 0.001
FFP transfused (mL, median (IQR))	0 (0, 0)	200 (0, 400)	< 0.001
Platelet transfused (U, median (IQR))	0 (0, 0)	0 (0, 0)	0.877

SD: standard deviation; BMI: body mass index; ASA: American Society of Anesthesiologists; FEV_1: forced expiratory volume in one second; IQR: interquartile range; FVC: forced vital capacity; hsCRP: high-sensitivity C-reactive protein; AIS: adolescent idiopathic scoliosis; RBC: red blood cell; FFP: fresh frozen plasma; -: not calculated. *Other etiologies encompass secondary scoliosis and other rare syndromic deformities.

Univariate logistic regression analysis results

The univariate logistic regression analysis revealed that non-idiopathic scoliosis (*OR* = 7.468, 95% *CI*: 2.878–25.474, *P* < 0.001) and ASA class Ⅲ–Ⅳ (*OR* = 3.696, 95% *CI*: 1.059–9.975, *P* = 0.019) were significant clinical risk factors. Additionally, greater preoperative main thoracic curve (*OR* = 1.016, 95% *CI*: 1.003 – 1.028, *P* = 0.013), lower FVC% predicted (*OR* = 0.974, 95% *CI*: 0.958–0.992, *P* = 0.003), and higher volumes of RBC (*OR* = 1.423, 95% *CI*: 1.196–1.670, *P* < 0.001) and FFP transfusions (*OR* = 1.001, 95% *CI*: 1.000 – 1.003, *P* < 0.001) were also significantly associated with an increased risk of PPCs (**Table 2**).

Table 2. Univariate logistic regression analysis of risk factors for PPCs

Variables	*OR* [95% *CI*]	*P* value
Age	0.737 [0.592–0.904]	0.005
ASA classification	3.696 [1.059–9.975]	0.019
Scoliosis type	7.468 [2.878–25.474]	< 0.001
Main thoracic curve	1.016 [1.003–1.028]	0.013
Lumbar curve	0.986 [0.969–1.001]	0.081
Thoracic kyphosis	1.015 [1.001–1.027]	0.018
FEV_1% predicted	0.976 [0.960–0.992]	0.004
FVC% predicted	0.974 [0.958–0.992]	0.003
Operation time	1.003 [1.000–1.006]	0.019
RBC transfusion	1.423 [1.196–1.670]	< 0.001
FFP transfusion	1.001 [1.000–1.003]	< 0.001
Correction rate of main thoracic curve	1.016 [1.003–1.029]	0.013
Correction rate of lumbar curve	0.989 [0.979–0.999]	0.033
Correction rate of thoracic kyphosis	1.002 [0.999–1.005]	0.086

OR: odds ratio; *CI*: confidence interval.

Multivariable logistic regression analysis results

To identify independent risk factors for PPCs while mitigating the impact of multicollinearity, variables that were statistically significant in the univariate analysis and of established clinical importance—specifically, scoliosis type, allogeneic RBC transfusion volume, main thoracic curve, and preoperative FVC% — were incorporated into a multivariable binary logistic regression model using enter method. Missing data were addressed using multiple imputation.

After adjusting for confounders, non-idiopathic scoliosis emerged as the only independent risk factor for PPCs (adjusted *OR* = 5.478, 95% *CI*: 2.017 – 19.148, *P* = 0.002). In contrast, preoperative FVC% predicted (adjusted *OR* = 0.993, 95% *CI*: 0.973 – 1.013, *P* = 0.497), main thoracic curve (adjusted *OR* = 1.002, 95% *CI*: 0.989 – 1.016, *P* = 0.736), and perioperative RBC transfusion volume (adjusted *OR* = 1.214, 95% *CI*: 0.976–1.489, *P* = 0.069) were all not significant predictors.

DISCUSSION

The present study retrospectively evaluated a large cohort of 1,234 adolescent scoliosis patients undergoing PSF to identify risk factors for PPCs. The overall incidence of PPCs was 2.35%, which is consistent with previous large-scale reports[10, 16]. The main finding of this study is that non-idiopathic scoliosis emerged as the sole independent predictor of PPCs, whereas preoperative FVC% and Cobb angle did not demonstrate independent predictive value. These findings suggest that the risk of PPCs in adolescent scoliosis may be primarily driven by the pathophysiological characteristics of the underlying etiology, while decreased pulmonary function and the severity of the scoliosis itself might serve more as secondary manifestations.

The clinical value of preoperative FVC% for assessing surgical tolerance in scoliosis patients has been a subject of considerable debate[17]. While historically relied upon for routine risk stratification, its universal predictive efficacy for PPCs is increasingly being chal-

lenged[13]. On one hand, some studies have reported that severe impairment in FVC% (e.g., < 40%) significantly predicts pulmonary complications; however, these findings are largely derived from specific cohorts with non-idiopathic etiologies, such as neuromuscular or congenital scoliosis[7, 18]. In these populations, a low FVC% genuinely mirrors intrinsic respiratory muscle weakness or severe alveolar hypoplasia. On the other hand, recent large-scale evaluations have questioned its routine utility. For instance, a landmark study by Burjek *et al*. suggested that preoperative PFT results were not associated with postoperative intubation or the need for intensive care in a general pediatric scoliosis population[13]. Our findings also indicate that the predictive validity of FVC% could be confounded by the underlying etiology. In patients with AIS, a reduced FVC% may represent a structural artifact, while their functional respiratory reserve often remains adequate to withstand surgical stress[19]. Risk stratification relying solely on FVC% values may overestimate the surgical risk in AIS patients, while potentially overlooking the latent vulnerabilities of non-AIS patients who might present with acceptable FVC% but possess complex etiologies.

The essential role of etiological classification is strongly supported by our data, showing that patients with non-idiopathic scoliosis had an over five-fold increased risk of PPCs compared to their AIS counterparts. From a pathophysiological perspective, non-idiopathic scoliosis can often arise secondary to systemic diseases and may accompany with multi-organ abnormalities[20]. Our sub-analysis demonstrated a heterogeneous risk profile within the non-AIS population. Congenital scoliosis accounted for 62.0% of all PPC events in our cohort. The higher incidence of PPCs in this group may be attributable to intrinsic thoracic cage anomalies that limit respiratory reserve. In addition, correction of these deformities often requires high-grade osteotomies, which are associated with increased surgical trauma, longer operative duration, and greater perioperative respiratory burden[21]. Syndromic scoliosis may also confer additional risk; for example, patients with Marfan syndrome may exhibit connective tissue fragility and altered pulmonary mechanics, predisposing them to complications such as pneumothorax[22]. Interestingly, only 1 PPC event (0.9%) occurred among the 109 patients with neuromuscular scoliosis in our cohort, which is lower than the range reported in the literature (2%–12%)[17,23]. This difference may be related to variation in disease composition. Our cohort included a lower proportion of patients with cerebral palsy, a population more susceptible to bulbar dysfunction and aspiration[23]. This case mix, together with preoperative optimization and standardized perioperative management, may have contributed to the relatively low incidence of PPCs observed. Separate multivariable analyses for each subgroup would be of interest; however, the limited number of events precluded such analyses due to insufficient statistical power and an increased risk of overfitting. Further studies with larger sample sizes are needed to explore these associations. Therefore, these subgroups were analyzed collectively as the non-AIS group, and the etiological classification is a variable that may comprehensively reflect the patient's systemic physiological status and respiratory compensatory capacity, thereby explaining the superior predictive efficacy over pulmonary function metrics as shown in this study.

Given the highly imbalanced ratio between the PPCs and the non-PPCs groups, the rationale for our variable selection in the multivariable model needs specific discussion. Although several other parameters, including patient age, ASA classification, operative time, and correction rates, demonstrated statistical significance in the univariate analysis, we restricted our multivariable model to four core predictors: scoliosis etiology, preoperative FVC%, main thoracic curve, and perioperative allogeneic RBC transfusion volume. This selective approach was based on a balance between clinical relevance and the statistical constraints of the events-per-variable rule[24]. With 29 positive PPC events, incorporating an excessive number of variables would precipitate model overfitting and yield unreliable effect estimates. Furthermore, substantial clinical collinearity exists among the univariate predictors[25]. For instance, a higher ASA classification is inextricably linked to non-idiopathic etiologies, while prolonged operative times, extensive blood loss, and specific correction rates are largely derivative of the severity of the preoperative main thoracic curve[26]. Therefore, the main thoracic curve and RBC transfusion volume can serve as proxies for fundamental anatomical complexity and the magnitude of perioperative surgical stress, respectively. Most importantly, the mandatory inclusion of FVC% and scoliosis etiology was essential to directly test the primary hypothesis of this study. This parsimonious modeling strategy may enhance model stability while preserving clinically relevant interpretability. Furthermore, the

consistent independent association of non-idiopathic etiology with PPCs across all imputed datasets provides additional support for the stability of the final model, despite the highly imbalanced case-to-control ratio.

Several limitations of this study should be acknowledged. First and foremost, although the overall sample size was large, the absolute number of PPC events was relatively small, which limited our ability to conduct more detailed subgroup analyses or propensity score matching, as such approaches would necessitate discarding a substantial amount of valid control data and further compromise statistical power for rare events. For example, some previous studies have proposed that severe pulmonary impairment (e.g., setting a threshold of FVC% < 40%) might serve as a cut-off value for predicting PPCs[27]. We initially attempted to explore this threshold effect; however, a review of our data showed that among the 29 patients who developed PPCs, only 1 patient had a preoperative FVC% < 40%. Dichotomizing a continuous variable under such low-frequency exposure would lead to model non-convergence or extreme statistical bias, so FVC% was kept as a continuous variable[24]. Therefore, the limited number of positive cases prevents us from completely ruling out an independent threshold effect for extremely severe pulmonary impairment. Second, as a retrospective, single-center study, inherent selection bias is inevitable. Also, detailed data regarding specific perioperative respiratory management interventions, including preoperative pulmonary rehabilitation, postoperative airway care, and chest physiotherapy, were not consistently recorded or adequately quantified in the medical records, making us unable to incorporate these essential preventive measures into the statistical models. Future prospective studies are needed to evaluate their potential protective effects on the incidence of PPCs. Lastly, preoperative PFT data were missing in 17.34% of the cohort due to the inability of some young or severely deformed patients to cooperate. Although we utilized multiple imputation to mitigate this issue, some influence on the final outcomes cannot be excluded. Future large-scale, prospective multicenter registries are needed to further investigate risk factors for adolescents receiving scoliosis correction surgery.

In conclusion, our study demonstrates that non-idiopathic scoliosis is an independent risk factor for PPCs following PSF in adolescents. After adjusting for the underlying etiology, preoperative FVC% and Cobb angle are not independent predictors of PPCs. Preoperative PFT results should be interpreted with caution, taking the underlying etiology into full consideration rather than relying solely on numerical thresholds.

ARTICLE INFORMATION

Supplementary materials

Available online at http://dx.doi.org/10.24920/004580.

Conflict of interest disclosure

All authors declare that they have no conflict of interests.

Author contributions

All authors had full access to the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. Chen WY obtained the funding, conceptualized and designed the study, and critically revised the manuscript. Zhan J, Hu A, and Wang HY were responsible for data collection. Zhan J contributed to formal analysis and drafted the manuscript. Zhang YL contributed to methodology. All authors reviewed and approved the final version of the manuscript.

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Data availability

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

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