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Article

Preoperative Predictors of Postoperative Pulmonary Complication Following Isolated Tricuspid Valve Surgery

Jie Wu[1], Na He[2,3], Yuqiang Wang[4], Hong Li[2,3,*]

[1]Department of Emergency Medicine, West China Tianfu Hospital, Sichuan University, 610041 Chengdu, Sichuan, China
[2]Nursing Key Laboratory of Sichuan Province, 610041 Chengdu, Sichuan, China
[3]West China School of Nursing, Sichuan University, 610041 Chengdu, Sichuan, China
[4]Department of Cardiovascular Surgery, Sichuan University West China Hospital, 610041 Chengdu, Sichuan, China
*Correspondence: lihong19681109@163.com (Hong Li)

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Abstract

Background: Postoperative pulmonary complications (PPC) are the most frequently observed complications following cardiac surgery, leading to extended hospital stays and significant medical and economic burdens. Although surgical interventions for tricuspid valve disease are increasingly common, few risk factors for PPC in the context of tricuspid valve surgery have been identified. Uncovering these factors would have valuable clinical implications in terms of prognosis. **Methods**: We conducted a single-center retrospective study to evaluate preoperative factors associated with susceptibility to PPC in patients undergoing tricuspid valve surgery between 2018 to 2023. Independent predictors of PPC were identified using regression analysis. **Results**: Of the 147 patients included in the study, 29.9% (44 cases) experienced PPC. No statistically significant differences were observed in surgical procedures between the groups. Regression analysis identified smoking status (odds ratio [OR]: 7.69, $p = 0.01$), severity grade of tricuspid regurgitation (TR) (OR: 26.56, $p < 0.01$), recent respiratory infection (OR: 78.52, $p < 0.01$), and pulmonary hypertension (OR: 13.60, $p < 0.01$) as independent risk factors for PPC following tricuspid valve surgery. Conversely, the 6-minute walk distance (6MWD) (OR: 0.99, $p = 0.01$) and tricuspid annular plane systolic excursion (TAPSE) (OR: 0.61, $p < 0.01$) were identified as independent protective factors. **Conclusion**: The incidence of PPC following tricuspid valve surgery was determined to be 29.9%. The identified predictors—smoking status, severity of tricuspid regurgitation, recent respiratory infections, pulmonary hypertension, as well as protective factors like 6MWD and TAPSE—can offer valuable insights for optimizing the preoperative physiological conditions in patients undergoing tricuspid valve surgery.

Keywords

tricuspid valve surgery; postoperative pulmonary complications; tricuspid regurgitation

Introduction

Tricuspid regurgitation (TR) affects approximately 36% of the elderly Chinese population diagnosed with degenerative heart valve disease [1,2]. This progressive disorder is characterized primarily by tricuspid annular dilatation and concurrent remodeling of the right ventricle and atrium [3]. Usually, tricuspid valve surgery serves as an auxiliary procedure on the mitral and/or aortic valves [4]. However, emerging evidence supports the proactive management of TR through early surgical repair or replacement to prevent severe right ventricular dysfunction [5]. Despite the frequency of these surgical interventions, they present numerous challenges, including the risk of severe right heart failure and subsequent end-organ damage prior to surgery, which contributes to increased mortality rates [6]. Perioperative outcomes typically focus on major adverse cardiac events, such as myocardial infarction, malignant ventricular arrhythmias, and stroke [7].

Recent studies suggest that postoperative pulmonary complications (PPC) surpass adverse cardiovascular events as the primary complications following cardiac surgery [8]. These complications, occur in approximately 10–25% of cardiac surgery patients, and lead to varying degrees of postoperative pulmonary dysfunction, which impacts functional recovery [9]. Consequently, PPC not only significantly increase the overall incidence rate of complications but also lead to extended hospitalization [10]. It is estimated that the duration of hospital stays for patients experiencing PPC is 1.5-fold longer and are six times more likely to require transfer to a rehabilitation center instead of returning home upon discharge [11]. Indeed, PPC are also more strongly associated with long-term postoperative mortality than cardiac complications, highlighting their critical impact on patient outcomes [12,13].

While preoperative variables associated with PPC in general cardiac surgery have been studied [14], there is a notable gap in understanding PPC, specifically following tricuspid valve surgery. Previous research has predominantly focused on cardiovascular and hepatic/renal outcomes post-tricuspid valve surgery, often neglecting PPC.

This oversight may be attributed to either the low incidence of PPC following tricuspid valve surgery or a general lack of awareness about such complications. Nonetheless, no substantial evidence supports these assumptions. Given the increasing number of TR cases requiring surgery, this study aims to quantify the incidence of PPC during tricuspid valve surgery and identify the relevant preoperative predictors. By doing so, we aim to enhance the preoperative physiological status of patients and mitigate the onset of PPC, thereby improving overall surgical outcomes.

Methods

Design

We executed a retrospective, single-center, observational study on a patient cohort who underwent isolated tricuspid valve replacement (TVR) or tricuspid valve repair (TVr) surgical procedures under general anesthesia and cardiopulmonary bypass. The study adhered to the principles of the Declaration of Helsinki and complied with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guideline.

Inclusion and Exclusion Criteria

Patients aged over 50 years who underwent elective isolated TVR/TVr surgical procedures from 2018–2023 were eligible for the study. The exclusion criteria included infective endocarditis, operation-related complications requiring reoperation, and severe non-pulmonary complications such as significant digestive tract hemorrhage, cerebrovascular accident, cardiac arrest, and wound infection. Between 2018 and 2023, we consecutively enrolled 190 patients anticipated to undergo elective tricuspid valvular surgery. Of these, 43 patients were excluded for various reasons: five were diagnosed with infective endocarditis; three experienced surgery-related complications; seventeen continued on medication as surgery was deemed unnecessary; and eighteen encountered serious non-pulmonary complications (Fig. 1).

Clinical Management Protocol

Patients underwent median sternotomy and cardiopulmonary bypass based on the tricuspid valve disease guidelines, which considered factors such as age, preoperative comorbidities, and recommendations from a multidisciplinary team (comprising a cardiologist, cardiovascular surgeon, echocardiography specialist, anesthesiologist, and two nursing staff members). Anesthesia induction was standardized in all patients with 1.5–2 mg/kg propofol (Sichuan Guorui Pharmaceutical Co., Ltd., Sichuan, China), rocuronium (Zhejiang Huahai Pharmaceutical Co., Ltd., Zhejiang, China) for muscle relaxation, and a continuous infusion of propofol and remifentanil (Humanwell Healthcare [Group] Co., Ltd., Hubei, China). Tracheal intubation and positive pressure ventilation were performed on all patients. The tidal volume was set to 6–8 mL/kg and the inspiratory-expiratory ratio was kept at 1:2. The respiratory rate was adjusted based on the patient's body weight, and the end-tidal carbon dioxide concentration was maintained at 30–35 mmHg.

Post-surgery, patients were routinely transferred to the intensive care unit (ICU) for close clinical monitoring. After weaning from mechanical ventilation in the ICU, patients were moved to the surgical ward, where they remained under observation until they were deemed fit for discharge.

Data Collection

Preoperative baseline characteristics, comorbidities, and clinical variables were collected from the Comprehensive Health Record. Details recorded for each patient included demographics (age, sex, body mass index), smoking history, New York Heart Association (NYHA) classification, left ventricle ejection fraction, TR severity grade, right ventricular function parameter (right ventricular [RV], right atrial [RA], tricuspid annular plane systolic excursion [TAPSE]), EuroSCORE II, preoperative arterial blood gas analysis on room air (PaO_2, $PaCO_2$, and SaO_2), 6-minute walk distance (6MWD), and pulmonary function test results (Forced expiratory volume in one second [FEV1]; forced vital capacity [FVC]; maximum inspiratory pressure [MIP]). Additionally, data on the history of previous cardiac surgery, presence of comorbidities (such as respiratory muscle weakness, hypertension, coronary artery disease, stroke, hyperlipidemia, type 2 diabetes, chronic kidney disease, chronic obstructive pulmonary disease, pulmonary hypertension, and respiratory infection in the past month), and type of surgery were noted.

Definition

Patients were screened by an interdisciplinary cardiac team, comprising two cardiac surgeons and one echocardiography specialist, based on echocardiographic findings. Transthoracic echocardiograms were performed and quantified according to Rebecca's proposed grading scheme. The vena contracta widths, along with the quantification of the effective regurgitant orifice area, were used to assess the degree of TR (mild, moderate, severe, massive, and torrential) prior to surgery [15].

All patients underwent preoperative pulmonary function tests in accordance with the criteria set by the American Thoracic Society. This included FEV1, FVC, and MIP. The actual measured values (FEV1 and FVC) were compared as a percentage to theoretical values derived from a Chinese population reference, established by Zhang *et al.* [16], using data from the 2012–2015 Chinese National Health

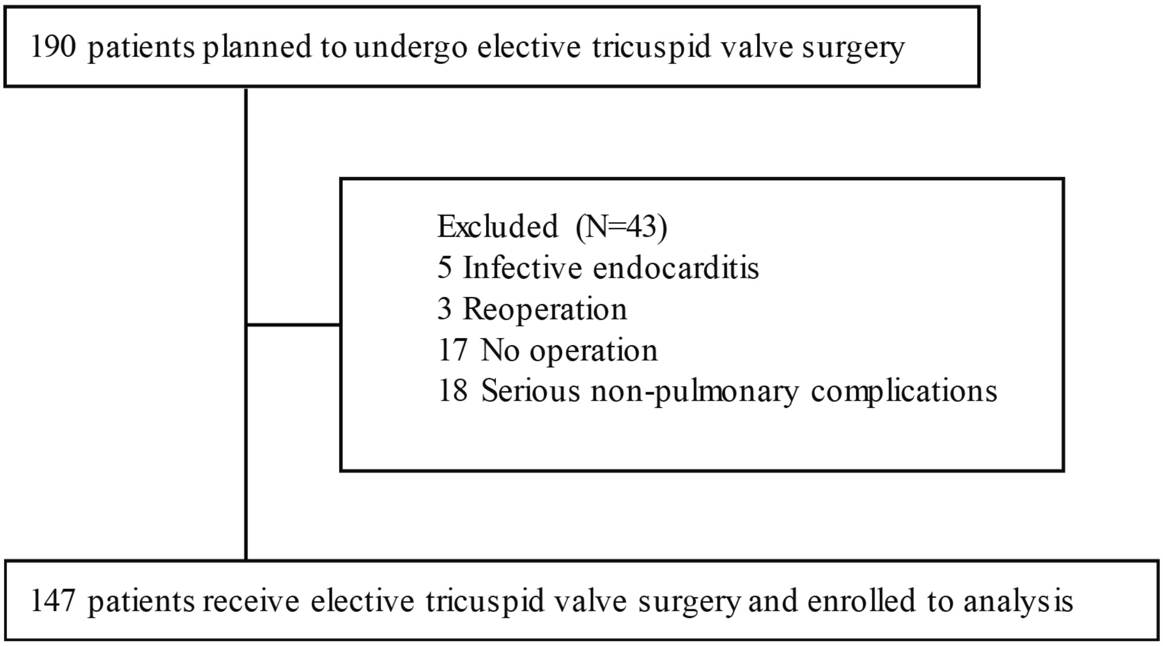

Fig. 1. Patient enrollment and study participation flowchart. This figure depicts the enrollment process and selection criteria for patients included in the study on tricuspid valve surgery. It starts with the total number of patients assessed for eligibility and details the exclusion and inclusion steps, resulting in the final participant group analyzed for postoperative pulmonary complications (PPC). Each decision point and patient count is clearly marked to demonstrate the filtering process that led to the cohort used in our analysis.

Survey. The study utilized the MIP reference values for various age groups, as proposed by Sclauser Pessoa *et al.* [17], to calculate MIP%. Additionally, patients' functional capacity was evaluated using the 6MWT, wherein patients were directed to walk as far as possible along a flat corridor within a 6-minute time frame [18]. All patients included in the study were required to complete this test upon admission.

Inspiratory muscle weakness, as per Evans' criteria, was characterized by maximum inspiratory pressure (MIP) values falling below 60% of the predicted value [19]. Hypertension was defined by either a consistently elevated blood pressure exceeding 140/90 mmHg, or evidence from antihypertensive medication records. Given the impracticability of performing coronary angiography on all patients, the diagnosis of coronary artery disease was inferred from patients past medical history, encompassing chronic coronary artery disease and acute coronary syndrome. All patients underwent preoperative brain computed tomography (CT) scans. Stroke was characterized as either ischemic stroke, intracerebral hemorrhage, or subarachnoid hemorrhage. Hyperlipidemia was classified into hypertriglyceridemia (triglyceride levels $\geq$150 mg/dL) and hypercholesterolemia (low-density lipoprotein cholesterol levels $\geq$180 mg/dL). Type 2 diabetes included patients exhibiting a fasting plasma glucose level of $\geq$126 mg/dL, a random or 2-hour plasma glucose level on oral glucose tolerance test of $\geq$200 mg/dL, a hemoglobin A1c level of $\geq$6.5%, or classic symptoms of hyperglycemia. Chronic kidney disease (CKD) was defined by a glomerular filtration rate below 60 mL/min/1.73 m^2 for a duration exceeding 3 months. Chronic obstructive pulmonary disease (COPD) was identified by a FEV1/FVC ratio below 70%. Pulmonary hypertension was characterized by a mean pulmonary artery pressure exceeding 25 mmHg. The patient's disease progression was tracked over the previous month to identify the presence of respiratory symptoms such as dyspnea, cough, and fever. This was supplemented by a review of medical consultation records from community hospitals and respiratory-specific antibiotic regimens [20]. Upon admission, all patients underwent chest radiography in either a supine or standing position. A comprehensive diagnosis of recent respiratory infections was made by radiologists based on the Atelectasis Score [21].

Outcomes

A retrospective analysis of PPC incidence was conducted at the point of discharge. The Melbourne Group Scale (MGS) was utilized for PPC screening, diagnosing PPC if four or more of the eight items were present [22]. Subsequently, patients were grouped into two categories: the 'PPC group' for those diagnosed with PPC and the 'non-PPC group' for those without PPC during hospitalization. One of the study's objectives was to examine the disparity in medical expenses between the two groups. Key outcomes of interest included length of stay (LOS), duration of ventilator usage, duration of antibiotic use, and the additional costs incurred due to PPC. These additional costs encompassed expenses related to the hospital ward, ventilation support, chest imaging, clinical laboratory tests, antibiotics, and medical consultations [23].

Statistical Analysis

To compare continuous variables between the PPC and non-PPC groups, we utilized the independent two-tailed Student's *t*-test or the Mann–Whitney U test. The Fisher's exact test was employed for the examination of categorical variables. Continuous data are displayed as the mean (standard deviation) and median (25th–75th percentile), while categorical variables are shown as number (percentages). For those patients unable to perform out-of-bed activities, their 6MWD was recorded as 0 m. To manage the presence of missing data (6MWD), we implemented multiple imputations [21]. A sensitivity analysis was conducted to assess the variance in results pre- and post-data imputation. Preoperative factors' association with PPC was investigated using logistic regression analysis. Initial covariates considered included age, smoking status, TR severity grade, 6MWD, FEV1, RV, TAPSE, MIP, respiratory infection in the past month, type 2 diabetes and pulmonary hypertension. Age, 6MWD, FEV1, RV, TAPSE and MIP were modelled as continuous variables, while the TR severity grade was categorized as mild, moderate, severe, massive, or torrential. The linearity of the logarithm of continuous variables was assessed with the Box-Tidwell test. Multicollinearity evaluation was performed using Pearson correlation coefficient statistics and by examining the Variance Inflation Factor and Tolerance of the multiple regression model with the same dependent and independent variables. The overall significance of the model was evaluated with the –2 log likelihood ratio test, and the model fit was assessed with the Chi-square test of the Hosmer-Lemeshow goodness of fit. We plotted Pearson and Deviance residuals against the predicted values to identify outliers and detect statistical leverage. The final covariates were determined to be smoking status, TR severity grade, 6MWD, TAPSE, respiratory infection in the past month, and pulmonary hypertension. All statistical tests were two-sided and performed at the 0.05 level of significance. All statistical analyses were carried out using SPSS version 25.0 (SPSS Inc, Chicago, IL, USA).

Results

Baseline Characteristics

Between January 2018 to January 2023, we recruited 190 patients for elective valvular surgery. Of these, 43 patients were excluded due to various reasons (Fig. 1). Of the remaining 147 patients included in the study, 25 (17.0%) underwent isolated tricuspid valve replacement (TVR), while 122 (83.0%) were subjected to isolated tricuspid valve repair (TVr) surgical procedures.

Preoperative comparisons between the PPC and non-PPC groups revealed no significant differences in terms of sex, New York Heart Association (NYHA) classification, left ventricular ejection fraction (LVEF), preoperative arterial blood gases in ambient air, and pulmonary function (Table 1). However, notable differences were observed in several clinical parameters. Patients in the PPC group were older (63.2 ± 12.1 *vs.* 57.4 ± 10.6 years, $p < 0.01$), had a more severe degree of TR ($p < 0.01$), a larger right ventricle (25.4 ± 5.0 *vs.* 23.4 ± 5.1 mm, $p = 0.03$), and poorer right heart systolic function (13.9 ± 3.5 *vs.* 17.4 ± 3.0 mm, $p < 0.01$), displayed a reduced capacity to walk (319.1 ± 127.9 *vs.* 374.8 ± 89.8 m, $p = 0.01$), and exhibited weaker inspiratory muscle strength (53.4 ± 20.2 *vs.* 61.2 ± 22.3 cmH_2O, $p = 0.04$). Furthermore, patients with PPC were more likely to have comorbidities including type 2 diabetes ($p < 0.01$), pulmonary hypertension ($p < 0.01$), and preoperative respiratory tract infection ($p < 0.01$). The frequency of isolated TVR/TVr surgeries was similar in both groups ($p = 0.05$) (Table 1).

A sensitivity analysis addressing the missing data highlighted mobility restrictions among the study participants. Specifically, seven patients in the PPC group and four in the non-PPC group were unable to perform the walking test due to their conditions. An independent samples *t*-test comparing the walking distances for those who could participate revealed significant differences between the groups (367.0 ± 109.8 *vs.* 291.5 ± 159.5 m, $p < 0.01$).

Primary Outcome

The incidence of PPC following tricuspid valve surgery was 29.9%, accounting for 44 out of the 147 cases undergoing the procedure. As per the Melbourne Group Scale (MGS) criteria, the four most frequent PPC findings were, in descending order of prevalence, included: elevated white blood cell counts ($>11.2 \times 10^9$/L) or the use of respiratory antibiotics, radiographic evidence of atelectasis or consolidation, clinical diagnosis of pneumonia or chest infection by the attending physician, and the presence of purulent sputum (yellow or green) (Table 2).

Burden of Medical Expenses

The PPC group, in comparison to the non-PPC group, experienced significantly longer durations of ICU stay (117.8 *vs.* 45.2 hours, $p < 0.01$) and postoperative hospitalization (16.0 *vs.* 7.0 days, $p < 0.01$) (Table 2). Additionally, patients with PPC required increased mechanical ventilation time (73.4 *vs.* 23.4 hours, $p < 0.01$), and incurred higher costs related to respiratory system care (3827.9 *vs.* 1236.47 Dollar, $p < 0.01$) (Table 3). Among the PPC group,

Table 1. Comparative overview of demographic, clinical, and preoperative characteristics between PPC and non-PPC groups.

	PPC (44)		non-PPC (103)		*p*
Age (years)	63.2	(12.1)	57.4	(10.6)	<0.01*
Male (%)	21	(47.7)	51	(49.5)	0.86
BMI (kg/m^2)	23.6	(4.0)	24.0	(3.3)	0.47
[a]Smoke	18	(40.9)	26	(25.2)	0.08
[a]NYHA classification (%)					
1	1	(2.3)	2	(2.0)	
2	14	(32.0)	51	(50.0)	0.12
3	28	(63.6)	50	(48.5)	
4	1	(2.3)	0	(0)	
LVEF (%)	58.4	(10.0)	61.2	(9.4)	0.12
[a]TR severity grade (%)					
Mild; Moderate; Severe	15	(34.1)	89	(86.4)	<0.01*
Massive	15	(34.1)	9	(8.7)	
Torrential	14	(31.8)	5	(4.9)	
[a]TR etiology (%)					
Primary	33	(75.0)	79	(76.7)	0.84
Secondary	11	(25.0)	24	(23.3)	
RV diameter (mm)	25.4	(5.0)	23.4	(5.1)	0.03*
RA diameter (mm)	47.1	(13.6)	43.6	(12.7)	0.13
TAPSE (mm)	13.9	(3.5)	17.4	(3.0)	<0.01*
EuroSCORE II	5.8	(3.3)	3.9	(2.8)	<0.01*
Preoperative SaO_2 (%)	94.6	(7.9)	96.5	(5.9)	0.11
Preoperative PaO_2 (mmHg)	88.0	(17.3)	88.0	(9.7)	0.99
Preoperative $PaCO_2$ (mmHg)	39.1	(6.2)	39.4	(3.8)	0.76
6MWD (m)	319.1	(127.9)	374.8	(89.8)	0.01*
FEV1 (L)	1.8	(0.8)	2.1	(0.7)	0.87
FEV1 (%)	70.8	(22.2)	73.6	(18.2)	0.43
FVC (L)	2.4	(0.9)	2.6	(0.7)	0.14
FVC (%)	70.5	(18.4)	72.7	(15.1)	0.46
MIP (cmH_2O)	53.4	(20.2)	61.2	(22.3)	0.04*
[a]History of median sternotomy	9	(20.5)	15	(14.6)	0.47
[a]Inspiratory muscle weakness	23	(52.3)	39	(37.9)	0.14
[a]Hypertension	13	(29.6)	34	(33.0)	0.85
[a]Coronary heart disease	4	(9.1)	7	(6.8)	0.73
[a]Stroke	4	(9.1)	9	(8.7)	1.00
[a]Hyperlipoidemia	13	(29.6)	24	(23.3)	0.42
[a]Type 2 diabetes	21	(47.7)	11	(10.7)	<0.01*
[a]CKD	9	(20.5)	15	(14.6)	0.47
[a]COPD	12	(27.3)	19	(18.5)	0.27
[a]Pulmonary hypertension	30	(68.2)	16	(15.5)	<0.01*
[a]Respiratory infection in the past month	11	(25.0)	4	(3.9)	<0.01*
TVR (%)	12	(27.3)	13	(12.6)	0.05
TVr (%)	32	(72.7)	90	(87.4)	

Data are presented as number (percentage) or mean (standard deviation). [a]Categorical data was analyzed using a Fisher's exact test. Continuous data were analyzed with independent two-tailed Student's *t*-tests. PPC, postoperative pulmonary complications; BMI, body mass index; NYHA, New York Heart Association; LVEF, left ventricular ejection fraction; TR, tricuspid regurgitation; RV, right ventricular; RA, right atrial; TAPSE, tricuspid annular plane systolic excursion; 6MWD, 6-minutes walking distance; FEV1, forced expiratory volume in one second; FVC, forced vital capacity; MIP, maximum inspiratory pressure; CKD, chronic kidney disease; COPD, chronic obstructive pulmonary disease; TVR, tricuspid valve replacement; TVr, tricuspid valve repair; *p-value < 0.05.

Table 2. Distribution of pulmonary complications as assessed by MGS criteria.

Items	Percentage of positive
(1) Chest radiograph report of atelectasis/consolidation	51.0%
(2) White blood cell of $>11.2 \times 10^9$/L or use respiratory antibiotics	89.8%
(3) Temperature >38 °C	28.6%
(4) Positive signs of infection on sputum microbiology	14.3%
(5) Production of purulent (yellow or green) sputum	35.4%
(6) SpO_2 <90% on room air	27.2%
(7) Diagnosis of pneumonia/chest infection by attending physician	38.1%
(8) Prolonged stay (>36 hours) or re-admission on the ICU	24.5%

MGS, Melbourne Group Scale; ICU, intensive care unit.

a total of 33 (75.0%) patients tested positive for sputum bacterial infection, with the majority occurring 1–3 days after surgery (60.5%) (Fig. 2). Furthermore, the duration of postoperative antibiotic usage was longer in the PPC group compared to the non-PPC group (13.5 *vs.* 2.7 days, $p <$ 0.01).

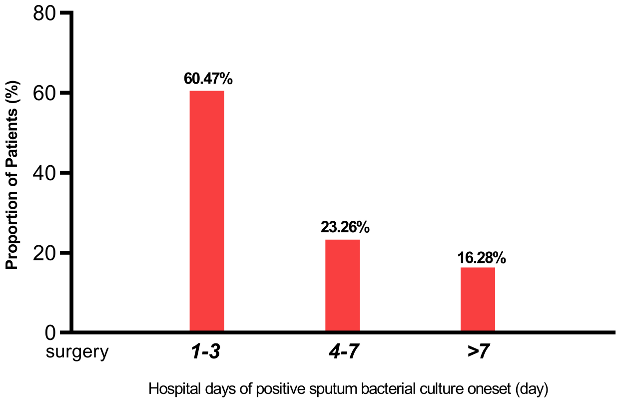

Fig. 2. Distribution of positive sputum bacterial infections following surgery. This figure illustrates the timeline and frequency of positive sputum bacterial infection among patients following tricuspid valve surgery. The x-axis represents the days post-surgery, with Day 0 being the day of the surgery itself. The y-axis shows the percentage of patients who tested positive for bacterial infection. Data points are divided into time intervals to demonstrate the proportion of positive tests occurring at each postoperative period.

Logistic Regression Analysis

Univariate analysis revealed several significant risk factors for PPC. Smoking emerged as a highly significant risk factor (odds ratio [OR]: 7.69, 95% confidence interval [CI]: 1.67–35.34, $p = 0.01$). The severity grade of TR, particularly at the torrential level, was also a strong predictor (OR: 26.56, 95% CI: 4.29–164.42, $p < 0.01$). Additionally, a history of respiratory infection in the past month substantially increased the risk (OR: 78.52, 95% CI: 7.69–801.21, $p < 0.01$), and pulmonary hypertension (OR: 13.60, 95% CI: 3.30–56.03, $p < 0.01$) were identified as risk factors in the multivariable model. Additionally, the six-minute walk distance (6MWD) (OR: 0.99, 95% CI: 0.99–1.00, $p = 0.01$) and tricuspid annular plane systolic excursion (TAPSE) (OR: 0.61, 95% CI: 0.48–0.76, $p < 0.01$) were independent protective factors for PPC (Table 4). The logistic model effectively classified 89.11% of the study subjects (Sensitivity 95.45%, Specificity 90.29%, area under curve (AUC) 0.96, $p < 0.01$) (Fig. 3).

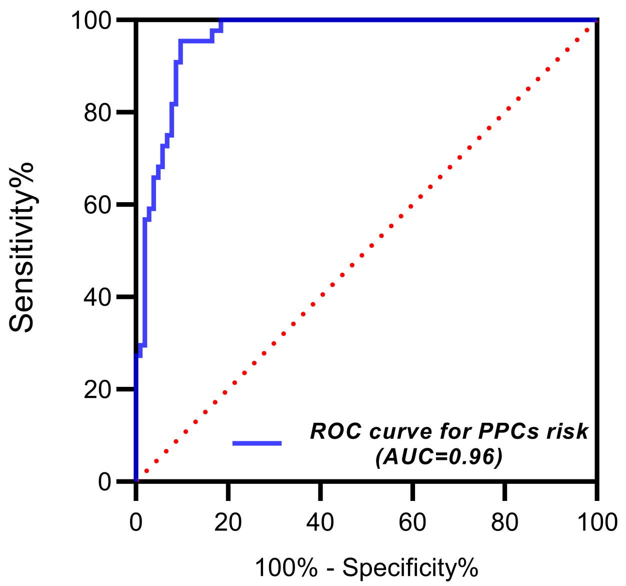

Fig. 3. ROC analysis of predictive model performance for postoperative pulmonary complications. This figure presents the receiver operating characteristic (ROC) curve for the logistic regression model predicting PPC. The model demonstrated high accuracy with an ability to correctly classify 89.11% of the study subjects, achieving a sensitivity of 95.45%, a specificity of 90.29%, and an area under the curve (AUC) of 0.96, indicating excellent predictive capability.

Table 3. Comparison of postoperative outcomes between PPC and non-PPC groups.

	PPC (44)		non-PPC (103)		p
Duration of intensive care unit (hour)	117.8	(79.3–185.8)	45.2	(23.5–68.2)	<0.01*
Length of postoperative Hospitalization (d)	16.0	(9.0–30.0)	7.0	(7.0–9.0)	<0.01*
Time of invasive ventilator usage (hour)	17.8	(9.7–87.9)	11.9	(0.0–17.8)	0.01*
Time of noninvasive ventilator usage (hour)	52.3	(45.5–84.0)	16.6	(0.0–33.3)	<0.01*
Total duration of mechanical ventilation (hour)	73.7	(58.0–105.4)	23.4	(0.0–44.1)	<0.01*
Oxygen therapy (hour)	113.7	(62.6–204.8)	29.5	(13.9–42.6)	<0.01*
Duration of antibiotics (d)	13.5	(7.1–23.9)	2.7	(1.8–3.3)	<0.01*
Additional cost in respiratory system (Dollar)	3827.9	(2058.9–4418.9)	1236.5	(1062.2–1491.5)	<0.01*

Data are presented as median (25th–75th) unless otherwise specified. Calculated using the Mann–Whitney U test (for length, duration, and cost). *p-value < 0.05.

Table 4. Risk and protective factors for postoperative pulmonary complications after tricuspid valve surgery.

Logistic Regression for Odds to Pulmonary Complication	Univariate OR (95% CI)		p	Multivariable OR (95% CI)		p
Age	0.91	(0.83–1.00)	0.06			
Smoke	12.57	(2.03–77.79)	0.01*	7.69	(1.67–35.34)	0.01*
TR severity grade (Mild; Moderate; Severe)			<0.01*			<0.01*
Massive	2.89	(0.47–17.69)	0.25	3.33	(0.78–14.11)	0.10
Torrential	23.55	(3.20–173.13)	<0.01*	26.56	(4.29–164.42)	<0.01*
6MWD	0.99	(0.99–1.00)	0.04*	0.99	(0.99–1.00)	0.01*
FEV1	1.07	(0.20–5.61)	0.93			
RV	1.12	(0.94–1.34)	0.21			
TAPSE	0.53	(0.39–0.74)	<0.01*	0.61	(0.48–0.76)	<0.01*
MIP	0.95	(0.90–1.00)	0.07			
Respiratory infection in the past month	142.54	(8.85–2295.97)	<0.01*	78.52	(7.69–801.21)	<0.01*
Type 2 diabetes	5.56	(1.06–29.08)	0.04*			
Pulmonary hypertension	14.60	(3.11–68.51)	<0.01*	13.60	(3.30–56.03)	<0.01*

TR, tricuspid regurgitation; 6MWD, 6-minutes walking distance; FEV1, forced expiratory volume in one second; RV, right ventricular; TAPSE, tricuspid annular plane systolic excursion; MIP, maximal inspiratory pressure; OR, odds ratio; CI, confidence interval. Independent predictors of postoperative pulmonary complications following tricuspid valve surgery calculated using backwards, stepwise multivariate logistical regression analysis with a p-value of 0.05 for entry and p-value of 0.10 for elimination. *p-value < 0.05.

Discussion

To the best of our knowledge, our study is the first report to specifically examine preoperative variables associated with pulmonary complications following isolated tricuspid valve surgery. We found the incidence of PPC was 29.9%, aligning with previous studies on cardiac surgery [9]. Our analysis identified several independent risk factors for PPC following tricuspid valve surgery: smoking, the severity grade of tricuspid regurgitation, previous respiratory infections, and pulmonary hypertension. Additionally, the 6MWD and TAPSE were found to be independent protective factors against the occurrence of PPC after tricuspid valve surgery.

PPC are well-documented adverse events during the perioperative period, commonly manifesting as pulmonary atelectasis and respiratory failure [10]. These complications not only lead to high-cost events that elevate in-hospital mortality rates but also significantly diminish patient quality of life [13]. Even minor PPC increase the utilization of healthcare resources. Cardiac surgeries, as invasive procedures, are particularly susceptible to these complications. Contributing factors such as general anesthesia, mechanical ventilation, and surgical manipulation can impair pulmonary function, thereby reducing effective coughing and deep breathing [24–26].

PPC significantly affect both short-term and long-term mortality rates, as well as overall outcomes following surgery. Patients undergoing non-cardiac thoracic surgery under general anesthesia who develop at least one PPC experience higher mortality rates, increased ICU admission, and prolonged hospital stays. Specifically, the 30-day mortality rate for patients with PPC ranges from 14% to 30%, compared to only 0.2% to 3% for those without PPC while the 90-day mortality rate stands at 24.4% for patients with PPC, versus 1.2% for those without [12,27]. These disparities in survival persist for up to five years. A large observational study from 2005 revealed stark long-term differences: 1-year mortality rates stood at 45.9% for patients with PPC compared to 8.7% for those without, and at five years the mortality rates were 71.4% *vs*. 41.1% [27].

The financial impact of PPC is also substantial, given the resources required for the diagnosis, treatment, and rehabilitation of affected PPC patients. It is estimated that PPC result in a 9% to 25% increase in total hospitalization costs [28]. Considering the high annual volume of surgeries and the preventability of most surgical adverse events, the implementation of systematic strategies to reduce the incidence of PPC is of significant public health importance. The development of PPC involves multifactorial causes, involving complex interactions between the patient, surgical procedure, and anesthesia factors. However, the management of these complications, rather than their mere occurrence, largely determines postoperative morbidity and mortality. Therefore, the focus of preoperative optimization strategies is to intervene early and reduce identified risks.

Our research underscores the significance of smoking (OR: 4.15, 95% CI: 1.20–14.35, $p = 0.02$) as an independent risk factor, confirming findings from previous studies [29]. Inhalation of chemical agents can result in airway burns, precipitating a spectrum of pathophysiological changes akin to acute respiratory distress syndrome, including bronchial inflammation, mucosal edema, epithelial cell detachment, and hypoxemia [30]. The perioperative smoking cessation guidelines, issued by the National Institute for Health and Care Excellence, stress both pharmacological and behavioral support to aid smoking cessation [31]. A cessation period exceeding 4 weeks prior to surgery reduces the incidence of PPC by 23%, and greater improvements are seen as the time is extended, with periods over 8 weeks reducing the incidence by 47% [31]. As a result, we strongly advocate that all patients scheduled for tricuspid valve surgery cease smoking at the earliest opportunity, irrespective of the anticipated surgical date.

A prospective cohort study discovered a correlation between respiratory infections—with symptoms like fever and the need for antibiotic treatments within one-month preceding surgery—and a range of adverse pulmonary outcomes such as pneumonia, pleural effusion, and pulmonary atelectasis [12]. Notably, 25% of patients in the PPC-group experienced a respiratory infection within a month before surgery, compared to only 3.9% in the non-PPC group, as evidenced by lobar atelectasis or bilateral lobar atelectasis from chest x-ray images or noted in medical records. Given the alarmingly high prevalence of community-acquired pneumonia in China, particularly among the elderly, it is suggested that elective tricuspid valve surgery patients with recent respiratory infections delay their operation by 1–2 weeks to improve pulmonary health. Additionally, for those already hospitalized, incorporating preoperative education on respiratory health could be beneficial. Supporting this approach, a study by Boden *et al*. [23] indicates that preoperative chest physiotherapy can significantly enhance patient fitness and effectively decrease the incidence of PPC.

Collaborative preoperative pulmonary rehabilitation, involving physiotherapists, has demonstrated comparable effectiveness in preventing the occurrence of PPC. This rehabilitation approach enhances the body's metabolic capacity, improves the systolic-diastolic cycle of respiratory muscles, alleviates muscle fatigue, and ultimately enhances lung function and overall functional capacity [32]. A meta-analysis involving 695 participants examined the impact of the treatment before cardiac or abdominal surgery [33]. The findings revealed a reduction in the incidence of both atelectasis and pneumonia (risk ratio (RR): 0.53, 95% CI: 0.34–0.82; RR: 0.45, 95% CI: 0.26–0.77; respectively) [33]. Similarly, Odor *et al*. [34] demonstrated that aerobic training prior to thoracic surgery significantly boosts patients' physiological reserve and reduces the risk of PPC, further validating the critical role of preoperative physical conditioning.

Our study is the first to report the incidence of PPC in isolated tricuspid valve surgery, identifying the degree of TR, pulmonary hypertension, and TAPSE as independent risk factors. We hypothesize that several mechanisms contribute to these complications. Notably, secondary TR, which affects 90% of patients, typically results from right ventricular remodeling caused by left-sided valvular or pulmonary hypertension [35]. Patients with pulmonary hypertension, especially when combined with significant right ventricular dysfunction, are at increased risk of severe hypoxemia, ventilation and circulatory failure due to hemodynamic instability during complex surgery, and mechanical ventilation [36].

Our team conducted a preliminarily systematic review the effects of inspiratory muscle training (IMT) in patients with pondus hydrogenii (PH). The results revealed a significant improvement in MIP by 18.89 cmH_2O (95% CI: 9.43–28.35, $p < 0.001$) and an increase in the 6MWD by 30.16 m (95% CI: 1.53–58.79, $p = 0.04$) [37]. These findings suggest that IMT is a promising intervention for enhancing the rehabilitation of patients with PH and may serve as a precursor to more structured exercise training. Moreover, IMT could significantly enhance functional capacity of patients undergoing isolated tricuspid valve surgery, potentially reducing the incidence of PPC [37].

Delayed presentation is prevalent among patients with TR due to the late onset of symptoms. The severity of TR is associated with compromised survival and the exacerbation of heart failure, yet tricuspid valve therapy is often initiated too late in clinical practice [5]. Furthermore, growing evidence suggests that severe right ventricular dysfunction correlates with an increased incidence of perioperative adverse events, further elevating the risk of PPC [38]. Our study corroborates these findings, demonstrating that patients in the PPC-group exhibited lower TAPSE values. This observation suggests impaired right ventricular systolic function is predictive of poorer postoperative outcomes.

Patients with secondary TR often experience increased left heart pressure, leading fluid to traverse the pulmonary capillary endothelium and accumulate in the interstitial and alveolar spaces, consequently, leading to decreased pulmonary diffusion, hypoxia, and dyspnea [39]. To prevent the progression of TR to more severe stages, early intervention is essential. Anti-heart failure treatment should be continued in TR patients with severe congestive heart failure. The primary objectives are to ameliorate symptoms of blood stasis and low cardiac output, restore normal oxygenation, optimize cardiovascular capacity, and enhance peripheral circulation. Surgical treatment should be delayed until heart failure conditions have stabilized [40].

Restricted capacity function is a fundamental clinical manifestation of heart failure and is recognized as a significant risk factor for postoperative adverse events. The severity of this functional limitation is directly correlated with the severity of heart failure [41]. The 6MWD test is widely employed to evaluate the functional capacity of patients with cardiovascular disease [42]. A meta-analysis identified clinically significant variances, ranging from 14.0–30.5 meters in the 6MWD among adults with respiratory and coronary artery disease [42]. In our study, we observed a notable disparity of 55.6 meters in 6MWD between two patient groups. Results from our regression model indicated that each 1-meter increase in 6MWD is associated with a 1% decrease in the probability of PPC. These findings suggest that enhancing perioperative capacity through targeted rehabilitation could significantly improve postoperative outcomes for patients undergoing tricuspid valve surgery. Previously, our team developed a three-day prehabilitation bundle protocol—comprising inspiratory muscle training, aerobic training, and educational components, referred to as the "TIME" program—for cardiac surgery patients [43]. This program has proven in reducing the incidence of PPC (OR: 0.60, 95% CI: 0.41–0.87) and reducing treatment costs (959.4 *vs.* 1319.2 Dollar, $p < 0.01$) [43]. Therefore, we advocate for the preoperative screening of patients at a high risk of PPC. By doing so, we aim to improve the patient's capacity to withstand surgical stress, minimize adverse events, and promote early functional recovery.

We observed that sputum infections occurred predominantly within 1–3 days following surgery, aligning with the findings reported by Serpa Neto *et al.* [44]. This frequent early occurrence is likely related to the patient's underlying disease condition, intraoperative airway management during anesthesia, and the initial management of organ dysfunction in the intensive care unit. Consequently, we advocate for the implementation of early rehabilitation and comprehensive respiratory management for postoperative patients to prevent the development of PPC and mitigate progression of respiratory distress. Early interventions for high-risk patients could include preoperative health education, inspiratory muscle training, aerobic exercise, intraoperative anesthesia and airway management, as well as early mobilization after surgery. These strategies are crucial and warrant further exploration in future studies.

Limitations

Our study has several limitations that should be acknowledged. Firstly, our study relied on multivariable regression analysis to identify independent influences on PPC. While this method establishes associations, it does not confirm causal relationships. Secondly, the absence of long-term postoperative follow-up limited our ability to assess the long-term functional capacity and quality-of-life impacts on both patient groups. Additionally, there was no further investigation on the impact of PPC on patient outcomes. To address this limitation, future studies should include extended follow-up periods to comprehensively capture these dimensions. The third limitation of our study is the omission of intraoperative and postoperative variables that may include additional PPC risk factors. These variables, such as operation time, blood transfusion regimen, anesthesia strategy, cardiopulmonary bypass duration, and ventilator management could potentially influence the occurrence of PPC. Although including these variables could enhance the predictive accuracy of our model, their inclusion might hinder the identification of high-risk preoperative populations, potentially inhibiting optimization. The fourth limitation of this study is the need for caution in interpreting the 6MWD as a protective factor. It should be noted that some patients with TR were too symptomatic to even get out of bed. To mitigate the impact of missing data, multiple imputation techniques were used. Importantly, the need for more tailored approaches to manage severely ill patients remains. Finally, the current study utilizes single-center retrospective data, which could bias our results, and limit the generalizability of our data. Therefore, caution is advised when interpreting our results. Future research should aim to replicate these findings across multiple centers and with larger sample sizes to confirm the multivariate predictors of PPC in patients undergoing tricuspid valve surgery.

Conclusion

In conclusion, this study successfully identified several independent predictors of PPC following tricuspid valve surgery, including smoking status, severity grade of TR, 6MWD, TAPSE, recent respiratory infections, and pulmonary hypertension. Clinicians are encouraged to utilize these predictors to assess surgical risk in patients with TR and to consider implementing preoperative optimization strategies to bolster physiological reserve and reduce the risk of PPC. Future research should explore and validate the efficacy of targeted interventions that aim to optimize preoperative risk factors, thereby reducing PPC incidence and improving surgical outcomes.

Availability of Data and Materials

The original contributions presented in the study are included in the article, and further inquiries can be directed to the corresponding author.

Author Contributions

JW conceived, designed, and planned the study. JW, NH and YW were responsible for acquisition, analysis, and interpretation of data. NH and YW interpreted results. JW, NH and YW drafted the report. HL as the corresponding author of this study, was primarily responsible for supervision, validation, visualization, writing - review & editing. JW and NH provided administrative, technical, and material support. All authors contributed to the article, data acquisition, and approved the submitted version. All authors contributed to editorial changes in the manuscript. All authors have participated sufficiently in the work to take public responsibility for appropriate portions of the content and agreed to be accountable for all aspects of the work in ensuring that questions related to its accuracy or integrity.

Ethics Approval and Consent to Participate

The Biomedical Ethics Committee of West China Hospital of Sichuan University (No.20201064) approved this retrospectively observational study of consecutive patients operated either TVR/TVr at West China Hospital. Participants were not required to sign a written informed consent form to participate in this study as it was a retrospective cohort study and did not involve an intervention.

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Conflict of Interest

The authors declare no conflict of interest.

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