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Development and Validation of a Clinical Prediction Model for Postoperative Pulmonary Complications in Patients Undergoing Spinal Tumor Surgery

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Abstract

Objective: To analyze the independent factors influencing postoperative pulmonary complications in patients with spinal tumors, develop a risk prediction model based on these factors, and evaluate its predictive performance, thereby providing a reference for the perioperative risk stratification of high-risk patients. **Methods:** A total of 245 patients with spinal tumors who underwent surgical treatment at our hospital between January 2024 and March 2026 were retrospectively included. Patients were divided into a complication group (n = 34) and a non-complication group (n = 211) according to the occurrence of pulmonary complications within 30 days after surgery. Nineteen clinical indicators covering the preoperative and intraoperative stages were collected as candidate predictors. Univariate analysis was first performed to screen variables that differed between groups, followed by multivariate binary logistic regression to identify independent risk factors. A random forest prediction model was then constructed using the selected variables, and its discriminative ability was assessed by the receiver operating characteristic curve and the area under the curve (AUC). **Results:** The overall incidence of postoperative pulmonary complications was 13.88% (34/245). Univariate analysis showed significant between-group differences in BMI (P = 0.045), operative duration (P = 0.0162), surgical approach (P < 0.001), and intraoperative blood transfusion volume (P < 0.001). Multivariate analysis identified surgical approach as an independent risk factor (OR = 3.969, 95% CI: 1.165 - 13.526, P = 0.0275; en bloc resection vs. conventional surgery), whereas BMI (OR = 0.906, P = 0.071) and massive transfusion (OR = 2.774, P = 0.095; vs. no transfusion) showed marginally significant trends toward protective and risk effects, respectively. The random forest model achieved an AUC of 0.6752 in the modeling cohort

and an AUC of 0.605 after five-fold internal cross-validation. The cross-validated Brier score was 0.152; for comparison, a logistic regression model using the same predictors yielded a cross-validated AUC of 0.663 with a Brier score of 0.108. **Conclusion:** Surgical approach is an independent high-risk factor for postoperative pulmonary complications after spinal tumor surgery, while BMI and massive transfusion show protective and risk-related trends, respectively. The constructed random forest model has limited discriminative ability and can be used as a perioperative tool for risk factor identification and auxiliary risk stratification. To achieve accurate individualized prediction, larger sample sizes and the incorporation of specialty-specific indicators such as pulmonary function are needed.

Keywords

Spinal Tumors, Pulmonary Complications, Risk Factors, Logistic Regression, Random Forest, Predictive Model

1. Introduction

Spinal tumors comprise two major types: primary and metastatic. In recent years, advances in imaging-based screening and prolonged survival among patients with malignant tumors have led to a continued increase in their detection. For patients with intractable pain caused by tumor compression, progressive neurological dysfunction, loss of spinal stability, or poor response to nonsurgical interventions, surgical resection of the lesion remains the core strategy for curative treatment or palliative symptom relief [1]. Postoperative pulmonary complications (PPCs) are not uncommon after spinal surgery and include atelectasis, pulmonary infection, acute respiratory failure, pleural effusion, and pneumothorax. Once PPCs occur, they often prolong hospitalization and increase costs and, in severe cases, may be life-threatening, making them a key factor limiting postoperative recovery [2] [3]. Spinal tumor surgery is typically characterized by a large tumor burden, extensive soft-tissue dissection, and substantial intraoperative blood loss; some cases require combined approaches and internal fixation reconstruction, resulting in a markedly higher risk of PPCs than that associated with routine surgery for degenerative spinal disorders [4]. Previous studies have mainly focused on risk factors for PPCs after surgery for scoliosis or degenerative spinal disease [5]. Reports specifically developing prediction models for patients with spinal tumors remain limited, and most have used traditional logistic regression nomograms [1]; the application of machine learning algorithms is still at an exploratory stage. Accordingly, this study retrospectively included 245 patients who underwent surgery for spinal tumors at our hospital, systematically analyzed risk factors for postoperative PPCs, and attempted to develop a random forest prediction model, with the aim of providing a reference for the early identification of high-risk individuals and the formulation of individualized lung-protective strategies in clinical practice.

2. Materials and Methods

2.1. General Information

A retrospective study design was adopted, and 245 patients who underwent surgery for spinal tumors at our hospital between January 2024 and March 2026 were selected as study participants. The inclusion criteria were as follows: 1) pathological diagnosis of primary or metastatic spinal tumor; 2) first-time resection of the tumor lesion with or without spinal internal fixation; 3) complete medical records, preoperative laboratory test results, surgical records, and postoperative follow-up data; 4) postoperative follow-up of ≥30 days, allowing definitive assessment of pulmonary complications; and 5) informed consent provided by the patients and their family members. This study was a single-center retrospective case study. All data were obtained from previously archived electronic medical records of the hospital, no intervention was performed on patients during the study, and all personal information was anonymized and de-identified, making it impossible to trace the data to specific individuals. This study was approved by the ethics committee of our hospital, with a waiver of informed consent. The exclusion criteria were as follows: 1) active pulmonary infection or acute exacerbation of chronic obstructive pulmonary disease before surgery; 2) concomitant end-stage multiple organ failure; and 3) preoperative requirement for mechanical ventilation. Patients were divided according to the occurrence of pulmonary complications within 30 days after surgery into a complication group (34 cases) and a non-complication group (211 cases). During the study period, patients who underwent surgery for spinal tumors at our hospital were screened for eligibility. After application of the exclusion criteria (active pulmonary infection or acute exacerbation of chronic obstructive pulmonary disease, concomitant end-stage multiple organ failure, or preoperative requirement for mechanical ventilation), and after exclusion of patients with incomplete medical records or loss to follow-up, 245 patients were ultimately included in the analysis. All 245 included patients had complete data for the variables analyzed. The number of patients excluded for each specific criterion was not systematically recorded in the retrospective database; this limitation, together with the requirement for complete records, is acknowledged as a potential source of selection bias.

2.2. Diagnostic Criteria and Study Measures

With reference to relevant literature [3], postoperative pulmonary complications were defined as the occurrence of any of the following within 30 days after surgery: 1) pneumonia, characterized by fever, abnormal leukocyte count, and purulent airway secretions accompanied by newly developed infiltrates on imaging; 2) atelectasis, indicated by segmental or lobar collapse on imaging accompanied by hypoxemia; 3) respiratory failure, defined as an arterial oxygen partial pressure ≤ 60 mmHg or the need for reintubation; 4) moderate-to-large pleural effusion requiring puncture and drainage; and 5) pneumothorax requiring closed thoracic drain-

age. During hospitalization, PPCs were identified through daily review of medical records, nursing notes, chest radiography and computed tomography reports, and arterial blood gas results by the attending surgical team; after discharge, all patients were followed up at the outpatient clinic or by structured telephone interview at 30 days postoperatively. All suspected PPCs were independently adjudicated by two investigators (an anesthesiologist and an orthopedic surgeon) according to the predefined criteria; disagreements were resolved by consensus discussion with a senior physician. Patients who developed more than one type of PPC were counted as a single event in the composite outcome, and the most clinically severe complication was recorded for descriptive purposes. Nineteen preoperative and intraoperative clinical variables were collected as candidate predictors: preoperative variables included age, sex, BMI, albumin, hemoglobin, ADL, NRS2002, smoking history, pain, number of chronic comorbidities, tumor classification, preoperative interventional embolization, and history of radiotherapy or chemotherapy; intraoperative variables included surgical site, surgical approach, pathological fracture, operative duration, blood loss, and transfusion volume. Surgical procedure type (modus operandi) was categorized as conventional surgery (including posterior decompression, curettage, and intralesional/piecemeal resection; reference group) versus en bloc resection (including total spondylectomy and combined anterior-posterior radical resection). Intraoperative allogeneic red blood cell transfusion volume was categorized as no transfusion (0 mL; reference group; n = 73, 6 PPCs), limited transfusion (<800 mL; n = 121, 12 PPCs), and massive transfusion (≥800 mL; n = 51, 16 PPCs). Postoperative drainage status was recorded as a descriptive clinical variable but was not included as a candidate predictor because the model was intended for perioperative risk assessment before the postoperative course unfolded.

2.3. Statistical Methods

Data analysis was performed using SPSS 26.0 and R 4.3.1. Normally distributed continuous variables were described as means ± standard deviations, and between-group comparisons were conducted using independent-samples t-tests. Categorical variables were presented as counts and percentages, and between-group differences were assessed using the χ^2 test or Fisher's exact test. Variables with $P < 0.05$ in univariate analysis were included in a multivariable binary logistic regression model, and model fit was evaluated using the likelihood ratio test. A random forest prediction model was constructed based on the variables selected through regression analysis, using the random Forest package in R. The model was set to grow 500 decision trees with mtry = 1 (the default for three candidate predictors); no additional hyper-parameter tuning was performed. Given the imbalance between complication and non-complication cases, no specific class-imbalance adjustment (e.g., class weighting or resampling) was applied. Model stability was assessed using stratified five-fold cross-validation. Within each fold, the random forest was trained on four folds and evaluated on the held-out fold; the optimal

cutoff value was determined using the Youden index on the training folds and then applied to the held-out fold. Of note, variable selection based on univariate and multivariable logistic regression was performed on the entire cohort before cross-validation rather than being nested within each fold; this may introduce a degree of optimistic bias and is acknowledged as a limitation. Discriminative performance was evaluated using the area under the receiver operating characteristic (ROC) curve (AUC). Calibration was assessed using the calibration intercept, calibration slope, and Brier score. For comparison, a multivariable logistic regression model using the same three predictors was also evaluated under the same cross-validation framework. From the optimal cutoff, sensitivity, specificity, accuracy, and the F1 score were calculated. A two-sided $P < 0.05$ was considered statistically significant.

3. Results

3.1. Univariate Analysis

Among the 245 patients, 34 developed postoperative pulmonary complications, yielding an incidence of 13.88% (34/245). Univariate analysis of 19 variables showed statistically significant differences for BMI (t-test, $P = 0.045$), operative duration (t-test, $P = 0.0162$), surgical approach (Fisher's exact test, $P < 0.001$), and intraoperative transfusion volume (χ^2 test, $P < 0.001$). In contrast, age, albumin, hemoglobin, sex, ADL, NRS2002, smoking history, pain, number of chronic comorbidities, tumor classification, interventional embolization, chemoradiotherapy, surgical site, pathological fracture, and intraoperative blood loss all had P-values > 0.05. Because operative duration was collinear with surgical approach and lacked independent predictive value, it was excluded. Ultimately, BMI, surgical approach, and intraoperative transfusion volume were included in the multivariate analysis. See Table 1. Postoperative drainage status was not included as a candidate predictor, as specified in Section 2.2.

3.2. Multivariable Logistic Regression Analysis

Three variables were included in the regression model, and the overall likelihood ratio test was statistically significant ($\chi^2 = 18.52$, $P = 0.00015$, pseudo-$R^2 = 0.1146$). After adjustment, surgical approach was an independent risk factor ($\beta = 1.3786$, OR = 3.969, 95% CI: 1.165 - 13.526, $P = 0.0275$), indicating that patients undergoing en bloc resection had 3.969 times the odds of PPCs compared with those undergoing conventional surgery (reference group). The PPC event rates were 10/21 (47.6%) in the en bloc resection group and 24/224 (10.7%) in the conventional surgery group. BMI showed a protective trend (OR = 0.906, 95% CI: 0.815 - 1.008, $P = 0.071$), with each 1-unit increase in BMI associated with an approximately 9.4% reduction in risk. Massive transfusion showed a trend toward increased risk (OR = 2.774, 95% CI: 0.838 - 9.183, $P = 0.095$), whereas limited transfusion was not associated with risk (OR = 1.185, 95% CI: 0.421 - 3.341, $P = 0.748$), both compared with the no-transfusion reference group. See Table 2.

Table 1. Univariate analysis of postoperative pulmonary complications.

variable	Testing method	P-value	Whether included in the multivariable analysis
BMI	t-test	0.045	Yes
Duration of surgery	t-test	0.0162	No (excluded)
Surgical approach	Fisher's exact probability	<0.001	Yes
Intraoperative blood transfusion volume	χ^2 test	<0.001	Yes
Age	t-test	0.3702	No
Albumin	t-test	0.246	No
Hemoglobin	t-test	0.4759	No
Gender	Chi-square test	0.8211	No.
ADL	Chi-square test	0.5713	No
NRS2002	Chi-square test	0.3298	No
Smoking history	Chi-square test	0.5706	No.
Number of comorbid chronic diseases	Chi-square test	0.0802	No
Tumor Classification	Chi-square test	0.4575	No
Surgical site	Chi-square test	0.2096	No
Intraoperative blood loss	Chi-square test	0.0509	No
Pain	χ^2 test	1.000	No
Preoperative interventional embolization	Fisher's exact test	0.4204	No
History of radiotherapy or chemotherapy	χ^2 test	0.4446	No
Pathological fracture	χ^2 test	0.8125	No

Table 2. Results of multivariable binary logistic regression analysis.

Variables	β	OR	95% CI	P-value	Expert interpretation
BMI	−0.098	0.906	0.815 - 1.008	0.071	Marginally significant, with a protective trend
Surgical approach	1.379	3.969	1.165 - 13.526	0.028	Independent risk factors
Transfusion volume (small)	0.170	1.185	0.421 - 3.341	0.748	Not statistically significant
Transfusion volume (massive)	1.020	2.774	0.838 - 9.183	0.095	Marginally significant, with a trend toward increased risk

3.3. Discriminative Performance of the Predictive Model

A random forest model was constructed using three variables. In the modeling cohort, the area under the ROC curve (AUC) was 0.6752, with an optimal cutoff value of 0.100, sensitivity of 100%, and specificity of 42.86%. After five-fold cross-validation, the AUC was 0.605. The optimal cutoff value determined by the Youden index was 0.360, at which the sensitivity was 57.14%, the specificity was 85.71%, the overall accuracy was 81.63%, and the F1 score was 0.4706. The cross-validated calibration intercept was −1.41 and the calibration slope was 0.08, with a Brier score of 0.152, indicating poor calibration with systematic overestimation of risk. For comparison, the multivariable logistic regression model built from the same

three predictors achieved a cross-validated AUC of 0.663, a Brier score of 0.108, a calibration intercept of −0.03, and a calibration slope of 0.98, indicating substantially better calibration than the random forest model. The model showed better discrimination for patients without complications (high specificity), but had a relatively high missed-diagnosis rate; therefore, it is recommended as an auxiliary tool for clinical assessment. See Table 3.

Table 3. Diagnostic performance of the random forest prediction model.

Metrics	Numerical	Indicators	Numerical
Modeling AUC	0.6752	Validation AUC	0.605
Modeling sensitivity	1.000	Validation sensitivity	0.571
Modeling specificity	0.429	Validation specificity	0.857
Optimal cutoff value	0.360	Accuracy	0.816
Calibration intercept	−1.41	Calibration slope	0.08
Brier score (RF)	0.152	Brier score (LR)	0.108
Cross-validated AUC (LR)	0.663	F1 score	0.471

4. Discussion

4.1. Incidence of Postoperative Pulmonary Complications

Among the 245 patients in this cohort, 34 developed PPCs within 30 days after surgery, corresponding to an incidence of 13.88%. This rate was markedly higher than the 4.3% - 5.7% reported for surgery for common degenerative spinal diseases [5], but was comparable to data from studies specifically involving patients with spinal tumors (11.2% - 15.8%) [1]. This may be explained by the fact that patients with spinal tumors are often bedridden for prolonged periods because of tumor compression and therefore have reduced pulmonary functional reserve. In addition, surgery typically requires extensive soft-tissue dissection, resection of the affected vertebrae, and internal fixation and reconstruction, resulting in substantial trauma and prolonged anesthesia; massive intraoperative blood loss and transfusion are also common. Together, these factors increase the risk of pulmonary complications [4]. Moreover, thoracic spinal tumor surgery often requires transthoracic or extrapleural approaches, which directly disturb the intrathoracic environment, leading to higher incidences of postoperative atelectasis, pleural effusion, and pneumothorax than in lumbosacral surgery [6]. The present data indicate that the burden of PPCs after spinal tumor surgery should not be underestimated. Clinically, such patients should be prioritized for perioperative lung-protective management, including comprehensive preoperative pulmonary function assessment, optimized intraoperative ventilation, and enhanced postoperative airway care and early mobilization.

4.2. Analysis of Influencing Factors

After adjustment for confounding factors, multivariable logistic regression showed

that the surgical approach was an independent risk factor for PPCs (OR = 3.969, P = 0.0275). Similar conclusions were reached in the nomogram for PPCs after spinal tumor surgery developed by Zou *et al.* [1] and in the multicenter survey by Yan *et al.* [2]. From a pathophysiological perspective, more invasive procedures, such as combined anterior-posterior approaches and total spondylectomy, require extensive dissection of the paraspinal muscles and prolonged retraction of the pleura and diaphragm, which not only restricts intraoperative ventilation but also increases the likelihood of pulmonary contusion. Prolonged operative time may also lead to anesthetic accumulation and diaphragmatic inhibition, weakening postoperative cough and sputum clearance and thereby predisposing patients to atelectasis and pulmonary infection [3]. The anterior transthoracic approach to the thoracic spine may also directly injure and rupture the pleura, causing pulmonary contusion and pleural effusion; the reported incidence of PPCs for this type of procedure is as high as 14.1% - 29.4% [6]. Therefore, for patients scheduled to undergo highly invasive procedures, preoperative pulmonary function testing and respiratory training should be implemented, intraoperative ventilation strategies should be optimized and the duration of one-lung ventilation should be minimized, and postoperative airway management and early rehabilitation exercises should be intensified.

In this dataset, BMI showed a potential protective tendency (OR = 0.906, P = 0.071), indicating that each 1-unit increase in BMI was associated with an approximately 9.4% reduction in the risk of PPCs. Traditionally, obesity, reflected by a high BMI, is generally regarded as an adverse factor for postoperative pulmonary complications because obese patients have reduced chest wall compliance and decreased functional residual capacity, thereby increasing the likelihood of postoperative atelectasis [7]. However, among patients with spinal tumors, a low BMI often indicates malnutrition and tumor-related wasting; these patients may have insufficient respiratory muscle strength and impaired immunity, which may instead increase the risk of postoperative pulmonary infection [8]. The prediction model developed by Zou *et al.* [1] also incorporated BMI and identified low BMI as a risk factor. It should be noted that, in the present study, the P-value for BMI was close to 0.05, and the confidence interval slightly crossed 1; therefore, this conclusion requires confirmation in studies with larger sample sizes. In clinical practice, for patients with low BMI, preoperative nutritional intervention should be emphasized to improve respiratory muscle function and overall immune status.

Massive intraoperative transfusion showed a trend toward increased risk in this cohort (OR = 2.774, P = 0.095), whereas no clear association was observed between low-volume transfusion and complications (P = 0.748). Several previous studies have reported an association between intraoperative allogeneic blood transfusion and postoperative infectious complications, as well as pulmonary complications, after spinal surgery [9]. A study based on an interpretable machine learning model likewise identified transfusion as a key predictor of postoperative pneumonia [10]. Mechanistically, this association may be related to transfusion-related

acute lung injury (TRALI), transfusion-associated circulatory overload (TACO), and immunosuppression induced by allogeneic blood products [11]. In the present cohort, massive transfusion did not reach statistical significance, which may be attributable to the limited number of positive events (only 34 cases) and the relatively low overall statistical power. Therefore, perioperative blood conservation should receive adequate attention in clinical practice. Strategies such as preoperative correction of anemia, intraoperative controlled hypotension, and cell salvage autologous transfusion may reduce the use of allogeneic blood and thereby lower the risk of pulmonary complications.

4.3. Development and Evaluation of the Prediction Model

Based on the three variables identified by multivariable logistic regression, this study developed a random forest prediction model. The model achieved an AUC of 0.6752 in the development cohort, which decreased to 0.605 after internal cross-validation, indicating room for improvement in discriminatory performance. This performance was inferior to the C-index of 0.755 reported for the nomogram by Zou *et al.* [1] and lower than the AUC levels of high-quality PPC models summarized by Huang *et al.* [3]. Notably, a multivariable logistic regression model using the same three predictors achieved a slightly higher cross-validated AUC (0.663 vs. 0.605) and substantially better calibration (Brier score 0.108 vs. 0.152; calibration slope 0.98 vs. 0.08) than the random forest, suggesting that the logistic model may be preferable in this small-sample setting. This may be attributable to three main factors. First, the sample size was limited (245 patients), with only 34 positive events; constrained by the events-per-variable ratio, random forests are prone to overfitting in small samples. Second, the included predictors were routine clinical indicators and did not include more predictive specialty-specific variables such as pulmonary function measures (FEV1 and FVC), smoking pack-years, and ASA classification [3]. Third, spinal tumors are highly heterogeneous, and the mechanisms underlying PPCs may differ between primary and metastatic tumors and across tumor locations; the absence of subgroup analyses may also have reduced predictive accuracy. In recent years, machine learning has been increasingly applied to the prediction of surgical complications, and random forests have attracted attention because of their ability to capture nonlinear relationships and interaction effects [12]. However, in settings with small samples and low event rates, they may not necessarily outperform traditional logistic regression [13]. Future work should expand the sample size through multicenter collaboration, incorporate specialty-specific indicators such as pulmonary function, and introduce SHAP values to enhance interpretability, thereby further optimizing the prediction tool.

5. Conclusion

Based on the above analysis, surgical approach was an independent high-risk factor for postoperative PPCs in patients with spinal tumors (OR = 3.969). BMI and

massive intraoperative blood transfusion showed protective and risk trends, respectively, but neither reached statistical significance. The random forest model constructed using these three variables had limited discriminative performance (internal validation AUC = 0.605) and, at this stage, may serve as a perioperative tool for risk factor screening and clinically assisted risk stratification. It should be noted that this study was a single-center retrospective investigation with a limited sample size and no external validation. In the future, multicenter studies with larger samples are needed to further enrich the predictor variables and optimize algorithmic performance.

Author Contributions

WJ: Conceptualization, methodology, data curation, formal analysis, and writing—original draft. YG: Supervision, resources, and writing—review and editing. All authors have read and approved the final version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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