Article

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Risk Factors for Persistent Atelectasis and Development of a Predictive Nomogram After Video-Assisted Thoracoscopic Lobectomy in Non-Small Cell Lung Cancer Patients: A Retrospective Cohort Study

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Background: On most postoperative imaging examinations, atelectasis after lobectomy is a transient finding. We focused on the more clinically consequential scenario: persistent collapse of at least one segment of the lung beyond the first postoperative week. These cases may delay mobilisation, impair secretion clearance, and increase the need for additional airway care after video-assisted thoracoscopic (VATS) lobectomy for non-small cell lung cancer (NSCLC). This study investigated perioperative predictors of this specific endpoint and used the identified factors to develop a nomogram.

Methods: We reviewed 1268 consecutive NSCLC patients treated with VATS lobectomy from January 2020 to December 2024. Persistent atelectasis meant radiographic collapse of at least one pulmonary segment for 7 or more postoperative days. Before modelling, 40 candidate predictors were coded. We then reviewed these predictors according to clinical domain, avoided retaining overlapping variables that represented the same construct, and performed 1000 bootstrap resamples for internal validation. Age, smoking exposure, forced expiratory volume in 1 second (FEV1), and operative time were additionally examined as continuous variables, and restricted cubic splines were used to assess possible nonlinear associations.

Results: Persistent atelectasis was recorded in 368 patients (29.0%). Twenty non-redundant variables were included in the adjusted analysis, corresponding to 18.4 events per variable. The final score retained age ≥65 years, smoking history ≥20 pack-years, chronic obstructive pulmonary disease (COPD), FEV1 <60% predicted, upper lobe resection, and operative time ≥180 minutes (all $p < 0.001$). The apparent area under the receiver operating characteristic curve (AUC) was 0.842 (95% confidence interval (CI) 0.818–0.865); the bootstrap-corrected AUC was 0.837 (95% CI 0.813–0.861). Calibration was acceptable (Hosmer-Lemeshow chi-square = 5.41, $p = 0.714$; slope = 0.92). Observed rates were 10.2%, 38.1%, and 79.0% in the low-, intermediate-, and high-risk groups (p for trend <0.001). Sensitivity analyses using continuous predictors produced similar discrimination, and spline analyses showed significant overall associations for age, smoking exposure, FEV1, and operative time.

Conclusion: In this cohort, persistent atelectasis was associated with pulmonary reserve, chronic airway disease, lobe removal, and the length of the operation. Because operative time is included in the score, the complete nomogram is best applied during perioperative or early postoperative care rather than preoperatively. Therefore, further multicentre validation remains necessary.

Keywords: non-small cell lung cancer; video-assisted thoracoscopic surgery; lobectomy; persistent atelectasis; risk factors; nomogram; predictive model

Introduction

For early non-small cell lung cancer (NSCLC), lobectomy remains a common curative operation. In our practice, as in many thoracic units, video-assisted thoracoscopic surgery (VATS) remains the usual approach when anatomy and oncologic requirements permit. The smaller incisions may promote recovery, but they do not eliminate the risk of postoperative lung collapse [1,2].

Atelectasis on the first postoperative radiograph is not unusual and often resolves after analgesia, ambulation, and breathing exercises are implemented. The cases that concern the ward team are those in which opacity persists beyond the first postoperative week, the patient has an ineffective cough, secretions accumulate, and bronchoscopy or prolonged oxygen therapy may become necessary [3,4,5,6,7].

This problem is often hidden within broader endpoints such as "postoperative pulmonary complications". Although these endpoints are useful for audit purposes, they do not identify which patients will still have visible lung collapse on postoperative day 7. Routine blood and coagu-

lation tests are also obtained from nearly all patients before surgery, but whether they add predictive value for this specific outcome remains uncertain [8,9,10].

Nomograms provide a practical means of converting multivariable regression models into individual risk estimates that can be applied in clinical settings [11]. We therefore used a consecutive cohort of patients undergoing VATS lobectomy to examine persistent atelectasis. The analysis was deliberately transparent: we counted the candidate predictors, reported the degrees of freedom, reduced obvious clinical overlap before adjustment, and then developed a perioperative nomogram using only the variables that remained. Because several final predictors were dichotomised for bedside use, their continuous forms were examined and restricted cubic splines were used to assess whether important nonlinear associations had been overlooked.

Methods

Study Design

This retrospective cohort study included 1268 patients with NSCLC who underwent VATS lobectomy in the Department of Thoracic Surgery of China Coast Guard Hospital of the Chinese People's Armed Police Force between January 2020 and December 2024. The study protocol was reviewed and approved by the Ethics Committee of China Coast Guard Hospital of the Chinese People's Armed Police Force (Approval No. Wulun [2025] 0704; Acceptance No. 2507171611777). The study was conducted in accordance with the Declaration of Helsinki. Given the retrospective design and the use of de-identified clinical data, the requirement for written informed consent was waived by the ethics committee. Patient information was handled confidentially according to institutional privacy and data-protection requirements.

Patients

Patients were eligible when they were 18–80 years old, had primary NSCLC classified according to the WHO thoracic tumour classification [12], had clinical stage I–IIIA disease according to the 8th edition of the TNM system [13], and underwent complete VATS lobectomy with systematic lymph-node dissection or sampling. Complete baseline, operative, laboratory, pulmonary-function, imaging, and postoperative outcome records were required. Imaging also had to be sufficient to determine whether a postoperative collapse persisted beyond postoperative day 7. Patients who received neoadjuvant chemotherapy or radiotherapy were not included.

We excluded conversion to thoracotomy, emergency surgery, prior ipsilateral thoracic surgery or major chest trauma, combined pulmonary procedures other than lobectomy, New York Heart Association class III–IV heart failure, forced expiratory volume in 1 second (FEV1) <30% predicted, active preoperative pulmonary infection or tuberculosis, missing key predictors, inadequate imaging for endpoint adjudication, death within 7 days from a non-pulmonary cause, and atelectasis already present before surgery [14,15].

Endpoint Definition

The endpoint was persistent postoperative atelectasis. In practical terms, this meant collapse of at least one pulmonary segment on radiography or CT that lasted for 7 consecutive postoperative days or longer [16].

Routine postoperative chest radiography was performed within 24 hours after surgery and subsequently according to clinical need, usually once daily while the chest tube remained in place. For patients with suspected or documented atelectasis, imaging was reviewed through postoperative day 7. When discharge occurred before day 7, a chest radiograph or CT obtained between postoperative days 7 and 14 was accepted for endpoint adjudication. CT findings took precedence when radiography and CT were performed within the same 24-hour period; otherwise, serial findings were interpreted chronologically. Persistent atelectasis required continued collapse on imaging obtained on or after postoperative day 7, whereas documented resolution before day 7 was classified as non-persistent atelectasis.

Early discharge was handled cautiously. If patients were discharged before postoperative day 7, post-discharge imaging examinations were reviewed; if persistence or resolution could not be established, the patient was excluded from the primary endpoint analysis.

Image assessments were performed independently by two thoracic radiologists who were blinded to the clinical or operative data. They first conducted separate evaluations, then resolved discrepancies through discussion. A senior radiologist adjudicated the indeterminate cases. Segmental, lobar, and complete collapse were recorded, but any of these counted as persistent atelectasis if the 7-day rule was met. The non-atelectasis group was reserved for patients with no postoperative collapse or documented clearing within 7 days.

Data Collection

We pulled data from electronic charts, CT reports, pulmonary-function reports, operative notes, and discharge summaries. Baseline variables covered age, sex, body mass index, smoking exposure, comorbid disease, tumour size, tumour site, histology, and clinical stage. Chronic obstructive pulmonary disease (COPD) required spirometric obstruction, FEV1/forced vital capacity (FVC) <0.70, in line with GOLD [17]. American Society of Anesthesiologists (ASA) physical status followed the ASA classification [18]. FEV1, FVC, FEV1/FVC, and diffusing capacity for carbon monoxide (DLCO) were interpreted according to ATS/ERS standards [14,15].

Table 1. Baseline clinical, pulmonary-function, and surgical characteristics of patients with and without persistent atelectasis.

Variable	Total cohort (n = 1268)	Atelectasis group (n = 368)	Non-atelectasis group (n = 900)	Test statistic	*p* value
Age (years), mean ± SD	62.5 ± 8.8	67.0 ± 7.8	60.7 ± 8.6	$t = 12.66$	<0.001
Age ≥65 years, n (%)	533 (42.0)	229 (62.2)	304 (33.8)	$\chi^2 = 86.77$	<0.001
Male sex, n (%)	749 (59.1)	232 (63.0)	517 (57.4)	$\chi^2 = 3.39$	0.066
BMI (kg/m^2), mean ± SD	24.4 ± 2.4	24.3 ± 2.3	24.5 ± 2.4	$t = –1.39$	0.166
BMI ≥25 kg/m^2, n (%)	546 (43.1)	154 (41.8)	392 (43.6)	$\chi^2 = 0.31$	0.577
Smoking ≥20 pack-years, n (%)	580 (45.7)	235 (63.9)	345 (38.3)	$\chi^2 = 68.57$	<0.001
COPD, n (%)	340 (26.8)	178 (48.4)	162 (18.0)	$\chi^2 = 122.76$	<0.001
Diabetes mellitus, n (%)	230 (18.1)	70 (19.0)	160 (17.8)	$\chi^2 = 0.27$	0.602
Hypertension, n (%)	540 (42.6)	178 (48.4)	362 (40.2)	$\chi^2 = 7.09$	0.008
Coronary artery disease, n (%)	145 (11.4)	54 (14.7)	91 (10.1)	$\chi^2 = 5.37$	0.020
Previous stroke, n (%)	56 (4.4)	20 (5.4)	36 (4.0)	$\chi^2 = 1.27$	0.259
ASA physical status III, n (%)	303 (23.9)	118 (32.1)	185 (20.6)	$\chi^2 = 19.03$	<0.001
FEV1 <60% predicted, n (%)	310 (24.4)	158 (42.9)	152 (16.9)	$\chi^2 = 95.93$	<0.001
FVC <70% predicted, n (%)	259 (20.4)	115 (31.3)	144 (16.0)	$\chi^2 = 37.37$	<0.001
DLCO <60% predicted, n (%)	299 (23.6)	122 (33.2)	177 (19.7)	$\chi^2 = 26.36$	<0.001
Histology	$\chi^2 = 3.30$	0.192			
Adenocarcinoma, n (%)	897 (70.7)	247 (67.1)	650 (72.2)		
Squamous cell carcinoma, n (%)	332 (26.2)	108 (29.3)	224 (24.9)		
Others, n (%)	39 (3.1)	13 (3.5)	26 (2.9)		
Clinical stage	$\chi^2 = 3.08$	0.214			
Stage I, n (%)	857 (67.6)	236 (64.1)	621 (69.0)		
Stage II, n (%)	253 (20.0)	79 (21.5)	174 (19.3)		
Stage IIIA, n (%)	158 (12.5)	53 (14.4)	105 (11.7)		
Tumor size >3 cm, n (%)	354 (27.9)	119 (32.3)	235 (26.1)	$\chi^2 = 5.03$	0.025
Upper lobe resection, n (%)	721 (56.9)	266 (72.3)	455 (50.6)	$\chi^2 = 50.27$	<0.001
Right-sided resection, n (%)	751 (59.2)	225 (61.1)	526 (58.4)	$\chi^2 = 0.79$	0.375
Operative time (min), median (IQR)	166 (145–193)	185 (160–210)	158 (138–184)	$Z = 9.86$	<0.001
Operative time ≥180 min, n (%)	452 (35.6)	198 (53.8)	254 (28.2)	$\chi^2 = 74.52$	<0.001
Estimated blood loss ≥100 mL, n (%)	400 (31.5)	145 (39.4)	255 (28.3)	$\chi^2 = 14.82$	<0.001
Pleural adhesion, n (%)	251 (19.8)	104 (28.3)	147 (16.3)	$\chi^2 = 23.41$	<0.001
Lymph node stations sampled ≥5, n (%)	435 (34.3)	142 (38.6)	293 (32.6)	$\chi^2 = 4.22$	0.040

ASA, American Society of Anesthesiologists; BMI, body mass index; COPD, chronic obstructive pulmonary disease; DLCO, diffusing capacity for carbon monoxide; FEV1, forced expiratory volume in 1 second; FVC, forced vital capacity; IQR, interquartile range; SD, standard deviation. Values are presented as mean ± SD, median (IQR), or number (%), as appropriate. Between-group comparisons were performed using an independent-samples *t* test, Mann–Whitney U test, chi-square test, or Fisher's exact test, as appropriate.

The laboratory panel was the usual preoperative set: blood counts, albumin, neutrophil-to-lymphocyte ratio (NLR), PLR, C-reactive protein, liver and renal biochemistry, fasting glucose, prothrombin time (PT), activated partial thromboplastin time (APTT), and D-dimer. Surgical variables included side, lobe, operative time, esti-

Table 2. Comparison of preoperative routine blood, nutritional, and inflammatory indicators between groups.

Variable	Total cohort (n = 1268)	Atelectasis group (n = 368)	Non-atelectasis group (n = 900)	Test statistic	*p* value
White blood cell count ($\times 10^9$/L)	6.4 ± 1.7	6.6 ± 1.8	6.3 ± 1.7	$t = 2.74$	0.006
Neutrophil count ($\times 10^9$/L)	4.0 ± 1.3	4.2 ± 1.4	3.9 ± 1.3	$t = 3.53$	<0.001
Lymphocyte count ($\times 10^9$/L)	1.8 ± 0.6	1.7 ± 0.6	1.8 ± 0.6	$t = –2.69$	0.007
Platelet count ($\times 10^9$/L)	231 ± 70	238 ± 72	228 ± 69	$t = 2.27$	0.023
Hemoglobin (g/L)	134.7 ± 14.0	133.5 ± 14.3	135.2 ± 13.8	$t = –1.94$	0.053
Albumin (g/L)	40.6 ± 4.0	39.9 ± 4.1	40.9 ± 3.9	$t = –4.00$	<0.001
Neutrophil-to-lymphocyte ratio	2.5 ± 1.2	2.8 ± 1.3	2.4 ± 1.1	$t = 5.19$	<0.001
Platelet-to-lymphocyte ratio	143 ± 59	150 ± 62	140 ± 58	$t = 2.66$	0.008
CRP (mg/L), median (IQR)	3.6 (1.9–6.8)	4.1 (2.2–7.6)	3.4 (1.8–6.4)	Z = 3.09	0.002

CRP, C-reactive protein; IQR, interquartile range; SD, standard deviation. Normally distributed variables are presented as mean ± SD, and skewed variables are presented as median (IQR). Between-group comparisons were performed using Student's *t*-test or Mann–Whitney U test according to data distribution.

Table 3. Comparison of preoperative biochemical and coagulation indicators between groups.

Variable	Total cohort (n = 1268)	Atelectasis group (n = 368)	Non-atelectasis group (n = 900)	Test statistic	*p* value
ALT (U/L), median (IQR)	23 (17–34)	24 (18–35)	23 (17–34)	Z = 1.24	0.215
AST (U/L), median (IQR)	22 (16–31)	23 (17–32)	21 (16–30)	Z = 2.51	0.012
Total bilirubin (μmol/L)	11.2 ± 5.0	11.4 ± 5.2	11.1 ± 4.9	$t = 0.95$	0.344
Serum creatinine (μmol/L)	69.8 ± 16.0	71.4 ± 16.5	69.2 ± 15.7	$t = 2.19$	0.029
BUN (mmol/L)	5.4 ± 1.4	5.5 ± 1.5	5.3 ± 1.4	$t = 2.20$	0.028
Fasting blood glucose (mmol/L)	5.8 ± 1.2	5.9 ± 1.3	5.7 ± 1.2	$t = 2.54$	0.011
PT (s)	11.7 ± 1.0	11.8 ± 1.1	11.7 ± 1.0	$t = 1.51$	0.132
APTT (s)	30.3 ± 3.7	30.6 ± 3.8	30.2 ± 3.6	$t = 1.73$	0.085
D-dimer (mg/L FEU), median (IQR)	0.33 (0.21–0.55)	0.38 (0.23–0.62)	0.31 (0.20–0.51)	Z = 4.12	<0.001

ALT, alanine aminotransferase; APTT, activated partial thromboplastin time; AST, aspartate aminotransferase; BUN, blood urea nitrogen; FEU, fibrinogen equivalent units; IQR, interquartile range; PT, prothrombin time.

mated blood loss, lymph-node stations sampled, and pleural adhesion. Postoperative events, including chest-tube duration, pneumonia, respiratory failure, unplanned intensive care unit (ICU) admission, bronchoscopy for secretion clearance, and 30-day readmission, were analysed after risk grouping and were not included as candidate predictors.

Before any regression was performed, 40 candidate predictors were coded. We kept this count visible because presenting only the six-variable nomogram could understate the amount of information considered during model development.

Statistical Analysis

R version 4.3.0 (R Foundation for Statistical Computing, Vienna, Austria) and SPSS version 26.0 (IBM Corp., Armonk, NY, USA) were used for statistical analysis. Continuous variables are shown as mean ± standard deviation or median with interquartile range, as appropriate; categorical variables are shown as counts and percentages. Normality was checked with the Shapiro-Wilk test.

For simple group comparisons, *t*-tests, Mann-Whitney U tests, chi-square tests, or Fisher exact tests were conducted. For the three risk categories, analysis of variance, Kruskal-Wallis tests, chi-square tests, or Fisher exact tests

were performed. The relevant test statistic was listed in the table next to the *p* value.

Each prespecified variable was examined in univariate logistic regression. Variables below $p < 0.10$ were not automatically included in the final model; instead, they were first reviewed with clinically important factors within the following prespecified domains: demographic characteristics, comorbidities, pulmonary function, tumour characteristics, operative factors, inflammatory/nutritional markers, biochemical indicators, and coagulation indicators.

Redundancy was assessed using both clinical content and pairwise association. Continuous variables with an absolute Spearman correlation coefficient ≥0.70 and categorical variables with a Cramér's V ≥0.50 were considered strongly overlapping. When two variables represented the same clinical construct, priority was given to the variable with clearer clinical interpretation, fewer missing values, lower VIF, and more stable regression estimates. Variables retained a priori because of established clinical relevance were not removed solely on the basis of univariate *p* values.

VIF <5 was considered acceptable. We report the screened count, the adjusted-stage count, the final predictor count, and the corresponding event-per-variable figures.

For continuous laboratory variables, linearity with the logit was examined using restricted cubic spline terms and by comparing linear and nonlinear specifications. Variables without evidence of nonlinearity were retained on their original continuous scale and expressed per clinically interpretable increment. When a nonlinear association was detected, the spline form was retained for sensitivity analysis; no data-driven cut point was introduced solely to improve significance.

The nomogram was drawn from the final multivariable logistic model with the rms package. Discrimination was summarised by area under the receiver operating characteristic curve (AUC). Calibration was checked using the calibration plot, intercept, slope, Brier score, and Hosmer–Lemeshow test. One thousand bootstrap samples were used for internal validation to estimate optimism in model performance, following current recommendations for clinical prediction-model development.

We also performed sensitivity analyses of the pulmonary function variables using three different models: COPD alone, FEV1 <60% predicted alone, and a combined model incorporating both variables.

To assess possible information loss caused by dichotomisation, age, smoking exposure, FEV1, and operative time were additionally entered as continuous variables. Age was expressed per 5-year increase, smoking exposure per 10 pack-years, FEV1 per 10-percentage-point decrease in predicted value, and operative time per 30-minute increase. The discrimination and calibration of this model were compared with those of the primary dichotomised model.

Restricted cubic spline analyses were then performed for age, smoking exposure, FEV1, and operative time using four knots placed at the 5th, 35th, 65th, and 95th percentiles. Overall associations and departures from linearity were tested separately.

Risk bands (<30%, 30%–60%, and >60%) were set before comparing observed event rates and were intended to reflect ordinary, enhanced, and high-intensity pulmonary management rather than to maximise a statistical contrast. Comparisons of hospital stay, chest-tube duration, pneumonia, respiratory failure, ICU admission, and bronchoscopy across risk groups were considered descriptive associations with the postoperative outcomes, and were not interpreted as evidence of independent predictive value for individual outcomes.

Results

Patient Characteristics and Incidence of Persistent Atelectasis

A total of 1268 patients met the eligibility criteria and were included in the analysis. Persistent atelectasis occurred in 368 patients (29.0%), whereas 900 patients (71.0%) did not meet the endpoint definition. Among patients with persistent atelectasis, the median time to radiographic resolution was 12 days (interquartile range (IQR), 10–15 days). The mean age of the overall cohort was 62.5 ± 8.8 years, and 749 patients (59.1%) were male. Adenocarcinoma was the most common histological subtype (n = 897, 70.7%), followed by squamous cell carcinoma (n = 332, 26.2%). The median operative time was 166 minutes (IQR, 145–193 minutes).

Baseline clinical, pulmonary-function, and surgical characteristics are presented in Table 1. Compared with patients without persistent atelectasis, those who developed the endpoint were older and more frequently had smoking exposure ≥20 pack-years, COPD, hypertension, coronary artery disease, ASA physical status III, impaired pulmonary function, tumour size >3 cm, upper lobe resection, operative time ≥180 minutes, estimated blood loss ≥100 mL, pleural adhesion, and sampling of at least five lymph-node stations. Sex, body mass index (BMI), diabetes mellitus, previous stroke, histological subtype, clinical stage, and operative side did not differ significantly between groups.

Preoperative haematological, nutritional, inflammatory, biochemical, and coagulation indicators are shown in Tables 2,3. White blood cell count, neutrophil count, lymphocyte count, platelet count, albumin, neutrophil-to-lymphocyte ratio, platelet-to-lymphocyte ratio, C-reactive protein, aspartate aminotransferase, serum creatinine, blood urea nitrogen, fasting blood glucose, and D-dimer differed significantly between groups. Haemoglobin and activated partial thromboplastin time showed borderline differences, whereas alanine aminotransferase, total bilirubin, and prothrombin time were similar between groups.

Table 4. Univariate logistic regression analysis of demographic, clinical, pulmonary-function, and surgical factors for persistent atelectasis.

Variable	OR	95% CI	*p* value
Age ≥65 years	3.23	2.51–4.16	<0.001
Male sex	1.26	0.98–1.62	0.066
BMI ≥25 kg/m^2	0.93	0.73–1.19	0.577
Smoking ≥20 pack-years	2.84	2.21–3.66	<0.001
COPD	4.27	3.27–5.57	<0.001
Diabetes mellitus	1.09	0.80–1.48	0.602
Hypertension	1.39	1.09–1.78	0.008
Coronary artery disease	1.53	1.07–2.19	0.020
Previous stroke	1.38	0.79–2.42	0.259
ASA physical status III	1.82	1.39–2.39	<0.001
FEV1 <60% predicted	3.70	2.83–4.85	<0.001
FVC <70% predicted	2.39	1.80–3.17	<0.001
DLCO <60% predicted	2.03	1.54–2.66	<0.001
Non-adenocarcinoma histology	1.27	0.98–1.65	0.070
Clinical stage II–IIIA	1.24	0.96–1.61	0.093
Tumor size >3 cm	1.35	1.04–1.76	0.025
Upper lobe resection	2.55	1.96–3.32	<0.001
Right-sided resection	1.12	0.87–1.43	0.375
Operative time ≥180 min	2.96	2.30–3.81	<0.001
Estimated blood loss ≥100 mL	1.64	1.28–2.12	<0.001
Pleural adhesion	2.02	1.51–2.69	<0.001
Lymph node stations sampled ≥5	1.30	1.01–1.67	0.040

ASA, American Society of Anesthesiologists; BMI, body mass index; CI, confidence interval; COPD, chronic obstructive pulmonary disease; DLCO, diffusing capacity for carbon monoxide; FEV1, forced expiratory volume in 1 second; FVC, forced vital capacity; OR, odds ratio.

Univariate Analysis of Candidate Predictors

All 40 prespecified candidate predictors were examined using univariate logistic regression. Tables 4,5 present the complete candidate set. Age ≥65 years, smoking history ≥20 pack-years, COPD, hypertension, coronary artery disease, ASA physical status III, FEV1 <60% predicted, FVC <70% predicted, DLCO <60% predicted, tumour size >3 cm, upper lobe resection, operative time ≥180 minutes, estimated blood loss ≥100 mL, pleural adhesion, and lymph-node stations sampled ≥5 were associated with persistent atelectasis.

Male sex, non-adenocarcinoma histology, and clinical stage II–IIIA met the prespecified screening threshold of $p < 0.10$ and were also evaluated in the multivariable model.

Among laboratory, biochemical, and coagulation indicators, higher white blood cell count, neutrophil count, platelet count, neutrophil-to-lymphocyte ratio, platelet-to-lymphocyte ratio, C-reactive protein, aspartate aminotransferase, serum creatinine, blood urea nitrogen, fasting blood glucose, and D-dimer were associated with greater odds of persistent atelectasis. Lower lymphocyte count and albumin were also associated with higher risk. Haemoglobin and activated partial thromboplastin time met the $p < 0.10$ screening threshold but did not reach conventional statistical significance.

Multivariable Logistic Regression Analysis

After evaluation within clinical domains and removal of clinically overlapping indicators, 20 variables were included in the adjusted analysis, corresponding to 18.4 events per adjusted-model variable. Six variables remained independently associated with persistent atelectasis: age ≥65 years, smoking history ≥20 pack-years, COPD, preoperative FEV1 <60% predicted, upper lobe resection, and operative time ≥180 minutes (Table 6).

Laboratory variables that were significant in the univariate analyses did not remain independently associated with the endpoint after adjustment for demographic, pulmonary-function, comorbidity, and operative factors. VIF values ranged from 1.04 to 1.62.

COPD and FEV1 <60% predicted were retained together because they provided related but non-identical clinical information. COPD represented chronic airway disease, whereas FEV1 represented measured ventilatory reserve.

Table 5. Univariate logistic regression analysis of laboratory, biochemical, and coagulation indicators for persistent atelectasis.

Variable	OR	95% CI	*p* value
White blood cell count (per 1 $\times 10^9$/L)	1.11	1.03–1.20	0.006
Neutrophil count (per 1 $\times 10^9$/L)	1.15	1.06–1.24	<0.001
Lymphocyte count (per 1 $\times 10^9$/L)	0.76	0.62–0.93	0.007
Platelet count (per 10 $\times 10^9$/L)	1.02	1.00–1.04	0.023
Hemoglobin (per 10 g/L)	0.91	0.83–1.00	0.053
Albumin (per 1 g/L)	0.94	0.91–0.97	<0.001
Neutrophil-to-lymphocyte ratio (per 1 unit)	1.32	1.19–1.47	<0.001
Platelet-to-lymphocyte ratio (per 10 units)	1.03	1.01–1.05	0.008
C-reactive protein (per 1 mg/L)	1.05	1.02–1.08	0.002
Alanine aminotransferase (per 10 U/L)	1.04	0.98–1.11	0.215
Aspartate aminotransferase (per 10 U/L)	1.08	1.02–1.15	0.012
Total bilirubin (per 1 µmol/L)	1.01	0.99–1.03	0.344
Serum creatinine (per 10 µmol/L)	1.09	1.01–1.18	0.029
Blood urea nitrogen (per 1 mmol/L)	1.10	1.01–1.20	0.028
Fasting blood glucose (per 1 mmol/L)	1.13	1.03–1.24	0.011
Prothrombin time (per 1 s)	1.10	0.97–1.25	0.132
Activated partial thromboplastin time (per 1 s)	1.03	0.99–1.06	0.085
D-dimer (per 0.1 mg/L FEU)	1.08	1.03–1.13	<0.001

CI, confidence interval; FEU, fibrinogen equivalent units; OR, odds ratio. Continuous variables were analyzed per specified clinically interpretable increment as shown in the table.

Sensitivity analyses using COPD alone, FEV1 alone, and both variables yielded similar discrimination and calibration.

Continuous-Variable Sensitivity Analysis

Age, smoking exposure, FEV1, and operative time were subsequently entered into a sensitivity model as continuous variables. Age was modelled per 5-year increase, smoking exposure per 10 pack-years, FEV1 per 10-percentage-point decrease in the predicted value, and operative time per 30-minute increase.

All four continuous variables remained associated with persistent atelectasis. Each 5-year increase in age was associated with a 31% increase in the odds of persistent atelectasis. The adjusted odds increased by 19% per 10 pack-years of smoking exposure, by 44% per 10-percentage-point decrease in FEV1, and by 27% per additional 30 minutes of operative time (**Supplementary Table 1**).

The continuous-variable model produced an AUC of 0.849 (95% CI, 0.826–0.872), compared with 0.842 for the dichotomised model. The difference in AUC was 0.007 and was not statistically significant ($p = 0.184$). The calibration slope was 0.94, the Brier score was 0.139, the AIC was 1186.4, and the BIC was 1248.2.

Restricted Cubic Spline Analysis

Restricted cubic spline analyses showed significant overall associations of age, smoking exposure, FEV1, and operative time with persistent atelectasis (all p for overall association <0.001). No significant departure from linearity was observed for age or smoking exposure, whereas modest evidence of nonlinearity was observed for FEV1 and operative time (**Supplementary Table 2** and **Supplementary Fig. 1**).

Nomogram Construction and Internal Validation

A perioperative nomogram prediction model was constructed using the six independent predictors retained in the final model: age ≥65 years, smoking history ≥20 pack-years, COPD, preoperative FEV1 <60% predicted, upper lobe resection, and operative time ≥180 minutes. Each predictor was assigned a weighted point value according to its regression coefficient, and the total score corresponded to the individualized predicted probability of persistent atelectasis after VATS lobectomy (Fig. 1A).

The nomogram demonstrated good discrimination, with an apparent AUC of 0.842 (95% CI: 0.818–0.865). At the optimal cutoff probability of 28.5% determined by Youden's index, the sensitivity was 78.8%, and the specificity was 74.1%. The positive and negative predictive values were 55.4% and 89.5%, respectively. Bootstrap internal validation with 1000 resamples yielded a corrected AUC of 0.837 (95% CI: 0.813–0.861), indicating limited optimism and acceptable internal reproducibility (Fig. 1B and Table 7).

Calibration analysis showed good agreement between predicted and observed probabilities. The Hosmer–Lemeshow goodness-of-fit test indicated good model fit ($\chi^2 = 5.41$, $p = 0.714$). The calibration intercept was 0.01 (95%

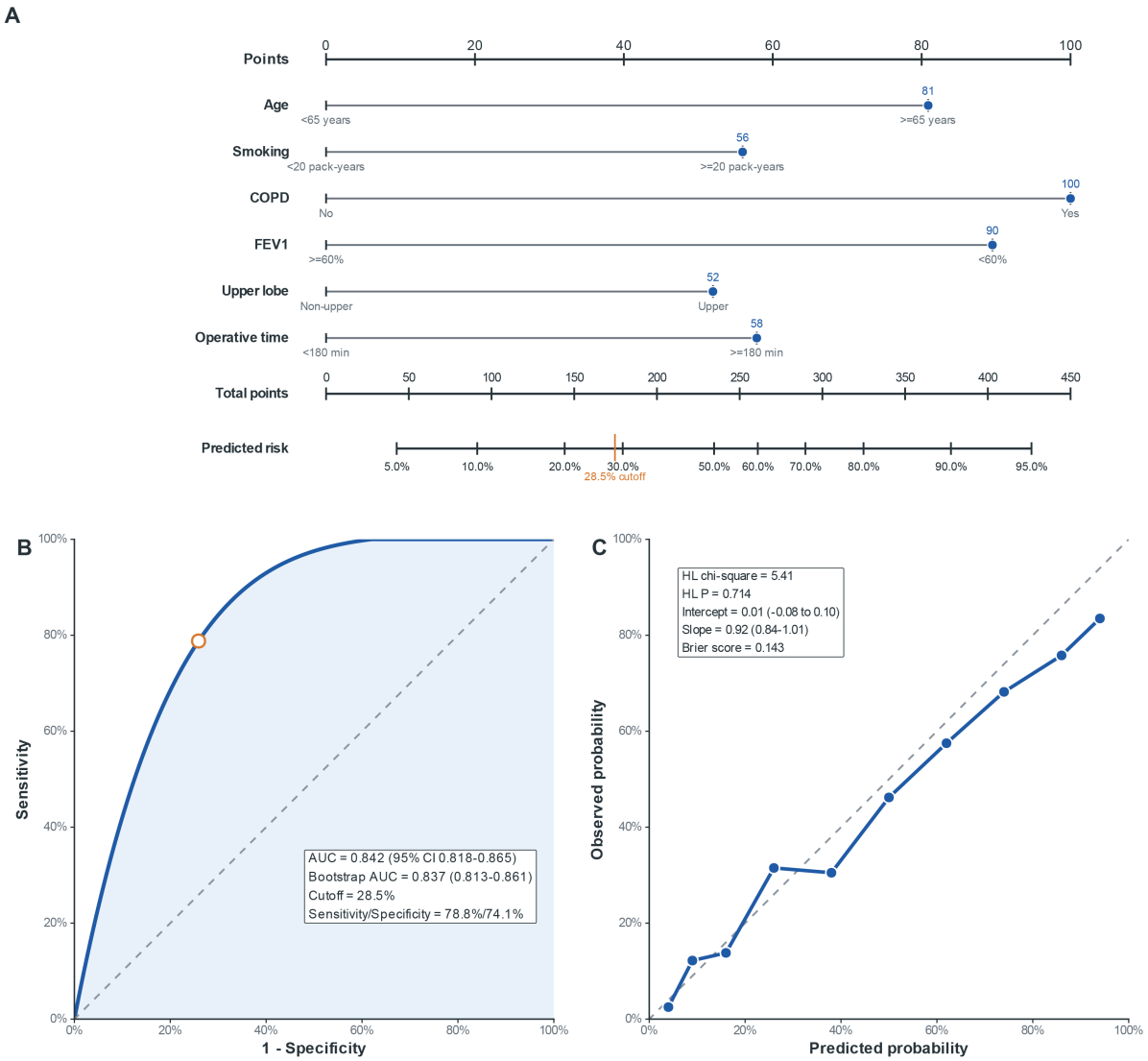

Fig. 1. Nomogram construction and internal validation for predicting persistent atelectasis after VATS lobectomy. (A) Nomogram based on six independent predictors: age ≥65 years, smoking history ≥20 pack-years, COPD, FEV1 <60% predicted, upper lobe resection, and operative time ≥180 minutes. The optimal cutoff probability was 28.5%. (B) ROC curve showing good discrimination, with an AUC of 0.842 (95% CI: 0.818–0.865) and a bootstrap-corrected AUC of 0.837 (95% CI: 0.813–0.861). At the optimal cutoff, sensitivity and specificity were 78.8% and 74.1%, respectively. (C) Calibration curve showing good agreement between predicted and observed probabilities, with Hosmer–Lemeshow χ^2 = 5.41, p = 0.714, calibration slope = 0.92, and Brier score = 0.143. AUC, area under the receiver operating characteristic curve; CI, confidence interval; COPD, chronic obstructive pulmonary disease; FEV1, forced expiratory volume in 1 second; VATS, video-assisted thoracoscopic surgery; ROC, receiver operating characteristic.

CI: –0.08 to 0.10), and the calibration slope was 0.92 (95% CI: 0.84–1.01). The Brier score was 0.143 (Fig. 1C and Table 7).

Clinical Utility, Risk Stratification, and Postoperative Outcomes

Decision curve analysis showed that the nomogram provided greater net benefit than the treat-all and treat-none strategies across a broad range of clinically relevant threshold probabilities (Fig. 2).

Patients were classified into low-risk (<30%), intermediate-risk (30%–60%), and high-risk (>60%) groups. The thresholds were specified before the observed outcome rates were compared. Persistent atelectasis occurred in 74 of 722 low-risk patients, 128 of 336 intermediate-risk patients, and 166 of 210 high-risk patients. The corresponding observed rates were 10.2%, 38.1%, and 79.0%, respectively (p for trend <0.001) (Table 8).

Table 6. Multivariable logistic regression analysis of candidate predictors for persistent atelectasis.

Variable	Adjusted OR	95% CI	*p* value
Age ≥65 years	3.46	2.55–4.69	<0.001
Male sex	1.05	0.74–1.48	0.784
Non-adenocarcinoma histology	1.09	0.78–1.52	0.611
Clinical stage II–IIIA	1.07	0.76–1.51	0.702
Smoking ≥20 pack-years	2.36	1.74–3.20	<0.001
COPD	4.64	3.31–6.49	<0.001
Hypertension	1.15	0.82–1.61	0.414
Coronary artery disease	1.13	0.73–1.75	0.581
ASA physical status III	1.19	0.82–1.74	0.363
FEV1 <60% predicted	3.95	2.81–5.55	<0.001
FVC <70% predicted	1.13	0.77–1.66	0.541
DLCO <60% predicted	1.21	0.85–1.73	0.292
Tumor size >3 cm	1.08	0.77–1.51	0.655
Upper lobe resection	2.22	1.61–3.06	<0.001
Operative time ≥180 min	2.43	1.80–3.28	<0.001
Estimated blood loss ≥100 mL	1.12	0.81–1.55	0.493
Pleural adhesion	1.20	0.83–1.73	0.336
NLR (per 1 unit)	1.08	0.96–1.21	0.201
Albumin (per 1 g/L)	0.98	0.94–1.02	0.313
D-dimer (per 0.1 mg/L FEU)	1.02	0.98–1.07	0.298

ASA, American Society of Anesthesiologists; CI, confidence interval; COPD, chronic obstructive pulmonary disease; DLCO, diffusing capacity for carbon monoxide; FEU, fibrinogen equivalent units; FEV1, forced expiratory volume in 1 second; FVC, forced vital capacity; NLR, neutrophil-to-lymphocyte ratio; OR, odds ratio.

Nomogram-defined risk groups were also associated with the subsequent postoperative course. Patients in the intermediate- and high-risk groups generally had longer hospital stays and chest-tube durations and higher observed rates of pneumonia, respiratory failure, unplanned ICU admission, and bronchoscopy for secretion clearance (Table 9).

These comparisons were descriptive. Because postoperative outcomes may be interrelated and may collectively reflect delayed recovery, these findings do not establish independent predictive value for each individual postoperative outcome.

Hospital stays increased from 7.8 ± 2.6 days in the low-risk group to 9.5 ± 3.1 days in the intermediate-risk group and 11.3 ± 3.2 days in the high-risk group. Chest-tube duration increased from 4.5 ± 1.5 days to 5.6 ± 1.8 days and 6.9 ± 2.0 days, respectively.

Pneumonia occurred in 5.4%, 14.6%, and 15.7% of patients in the three groups. Respiratory failure occurred in 1.7%, 3.3%, and 6.2%, whereas unplanned ICU admission occurred in 2.5%, 6.3%, and 10.5%, respectively. Bronchoscopy for secretion clearance was performed in 4.3%, 9.8%, and 16.2% of patients. The difference in 30-day readmission was not statistically significant.

Discussion

In this cohort of 1268 patients undergoing VATS lobectomy for NSCLC, nearly one third developed persistent atelectasis. Six independent predictors remained in the final model: age ≥65 years, smoking history ≥20 pack-years, COPD, FEV1 <60% predicted, upper lobe resection, and operative time ≥180 minutes. Although these variables are familiar to thoracic surgeons and anesthesiologists, the present study brings them together for a more specific endpoint: lung collapse that remains evident beyond the first postoperative week.

The incidence of persistent atelectasis in this study was 29.0%, which falls within the range reported for pulmonary complications after lung resection [3,4,16,19]. This rate also reflects the definition of the study endpoint. Transient collapse on early postoperative imaging was not enough; atelectasis was required to persist for at least 7 days. Clinically, this distinction matters. A small early opacity may resolve with analgesia, early ambulation, and respiratory exercises. In contrast, persistent atelectasis is more likely to be associated with secretion retention, repeated imaging assessments, delayed chest-tube removal, or the need for bronchoscopy, and may increase the risk of pneumonia or respiratory failure [20]. The higher-risk groups also experienced a less favourable postoperative

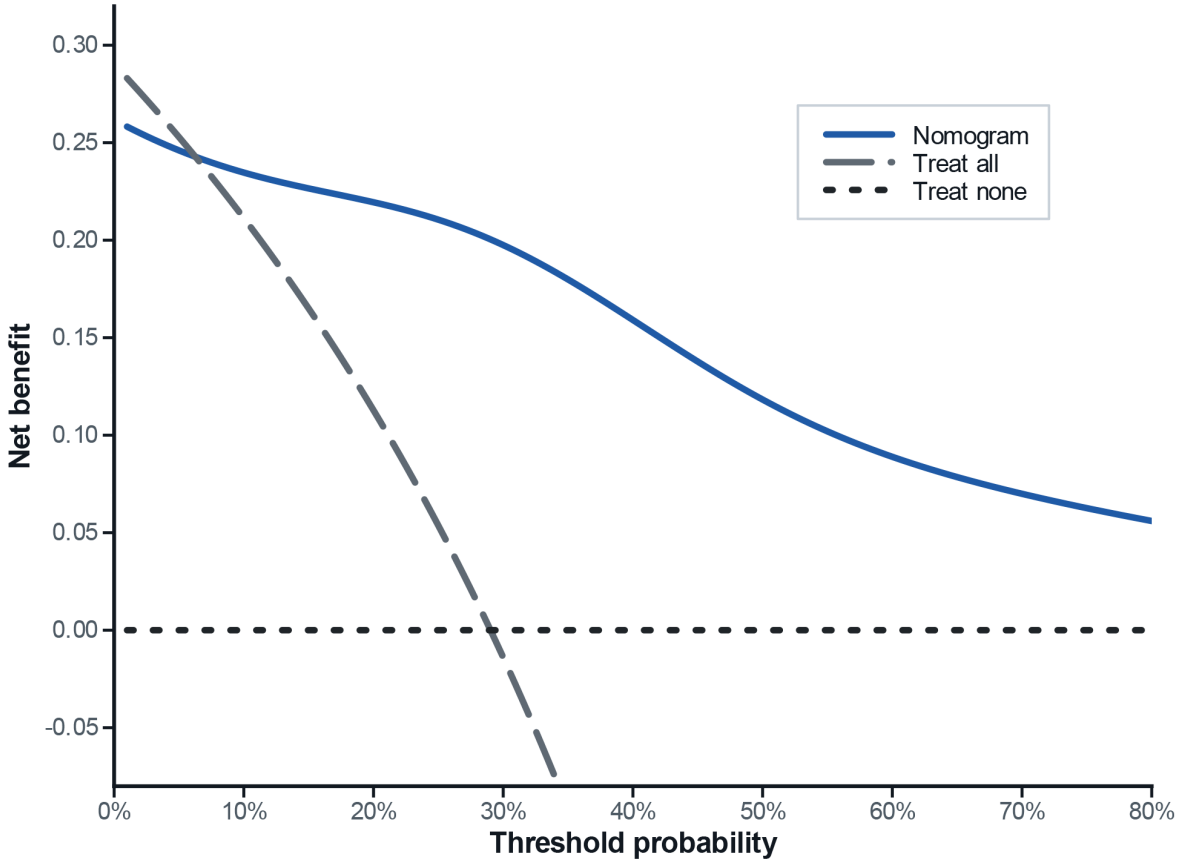

Fig. 2. Decision curve analysis. Decision curve analysis showed that the nomogram provided greater net benefit than treat-all or treat-none strategies across a broad range of clinically relevant threshold probabilities.

course, although these comparisons were descriptive and should not be interpreted as evidence that the nomogram independently predicted each postoperative outcome.

Age was one of the strongest predictors. Older patients often have weaker coughs, reduced chest wall compliance, lower respiratory muscle reserve, and less effective mucociliary clearance [21,22]. These changes may be well compensated before surgery but become evident after single-lung ventilation, pain, reduced mobility, and partial loss of lung volume. Older age is also a marker for frailty and coexisting disease, even when these factors are not fully captured by routine preoperative variables [23]. For this reason, the age effect should not be interpreted simply as a number on the chart, but as a broader indicator of limited postoperative respiratory reserve. The continuous-variable sensitivity analysis supported this interpretation: the odds of persistent atelectasis increased with advancing age, and restricted cubic spline analysis showed no significant departure from linearity.

Smoking history was another important component of the model. Heavy smoking adversely affects airway secretions, ciliary function, bronchial reactivity, and small-airway resistance [24,25,26]. These effects may persist even when patients stop smoking shortly before surgery. In clinical practice, smoking history often overlaps with COPD and impaired pulmonary function, but it still carries additional information about airway condition and secretion burden. The present findings therefore support the continued emphasis on smoking history when assessing respiratory risk before lung cancer surgery. Smoking exposure remained significant when modelled continuously, and the spline analysis suggested an approximately linear dose–response association rather than a clear biological threshold at 20 pack-years.

COPD showed the highest odds ratio in the final model. This is not surprising as patients with COPD often enter surgery with uneven ventilation, mucus retention, small-airway obstruction, and reduced expiratory flow. After lobectomy, these baseline problems may be amplified by pain, anesthesia, chest-tube irritation, and difficulty clearing secretions [17,27]. Preoperative pulmonary rehabilitation has been reported to improve perioperative respiratory outcomes in patients undergoing lung cancer surgery [28].

FEV1 <60% predicted also remained independently associated with persistent atelectasis. Pulmonary-function indices, including FEV1 and DLCO, are commonly used to

Table 7. Performance metrics of the nomogram prediction model.

Performance metric	Value
Number of candidate predictors screened	40
Candidate predictor degrees of freedom	40
Number of variables entered into adjusted multivariable model	20
Events per adjusted-model variable	18.4
Total sample size/events	1268/368
Number of final nomogram predictors	6
Events per final predictor	61.3
AUC (95% CI)	0.842 (0.818–0.865)
Bootstrap-corrected AUC (95% CI)	0.837 (0.813–0.861)
Estimated optimism in AUC	0.005
Optimal cutoff probability (%)	28.5
Sensitivity at optimal cutoff (%)	78.8
Specificity at optimal cutoff (%)	74.1
Positive predictive value (%)	55.4
Negative predictive value (%)	89.5
Brier score	0.143
Hosmer-Lemeshow χ^2	5.41
Hosmer-Lemeshow *p* value	0.714
Calibration intercept (95% CI)	0.01 (–0.08 to 0.10)
Calibration slope (95% CI)	0.92 (0.84–1.01)

AUC, area under the receiver operating characteristic curve; CI, confidence interval. The optimal cutoff was determined using Youden's index; internal validation was performed using 1000 bootstrap resamples. Candidate predictor degrees of freedom were counted after prespecified coding of variables used in the univariate screening framework.

Table 8. Risk stratification and observed atelectasis rates.

Risk category	Number of patients	Predicted risk range (%)	No. with persistent atelectasis	Observed atelectasis rate
Low risk	722	<30	74	10.2%
Intermediate risk	336	30–60	128	38.1%
High risk	210	>60	166	79.0%
p value for trend				<0.001

Chi-square test for trend was used to compare observed atelectasis rates across the three risk categories. The thresholds of <30%, 30%–60%, and >60% were prespecified as clinically interpretable risk categories before comparison of observed outcome rates and were not selected post hoc to maximize group separation.

estimate respiratory risk after lung resection, although their predictive value may vary across surgical populations and procedures [29,30]. Although COPD and FEV1 are closely related, they capture different clinical information. COPD is a disease diagnosis, whereas FEV1 reflects the measured ventilatory reserve available to the patient before surgery. Some patients with COPD may maintain preserved FEV1, whereas reduced FEV1 may result from causes other than COPD. In this cohort, the variance inflation factors were low, and sensitivity analyses using COPD alone, FEV1 alone, or both variables showed stable model performance. Retaining both variables was therefore reasonable, although some conceptual overlap remains. When FEV1 was analysed continuously, lower values remained associated with greater risk. The spline analysis suggested modest nonlinearity, indicating that the association was not fully captured by a single linear term, although the direction was consistent with the primary model. Structured pre- and postoperative rehabilitation may further reduce postoperative pulmonary complications and shorten hospital stay [31].

Upper lobe resection was another independent risk factor. The remaining lung must re-expand to occupy the postoperative thoracic space, and this process may differ according to the lobe removed. After upper lobectomy, changes in residual lung position, pleural pressure, bronchial angulation, and chest-cavity configuration may make complete re-expansion more difficult in some patients [32,33]. From a practical standpoint, patients undergoing upper lobectomy may deserve closer attention to early lung expansion and airway clearance, especially when other risk factors are present.

Operative time ≥180 minutes was retained in the nomogram, but its interpretation requires caution. A longer operative time may reflect adhesions, complex anatomy,

Table 9. Postoperative outcomes stratified by nomogram-based risk category.

Outcome	Total cohort (n = 1268)	Low risk (n = 722)	Intermediate risk (n = 336)	High risk (n = 210)	Test statistic	*p* value
Hospital stay (days), mean ± SD	8.8 ± 3.1	7.8 ± 2.6	9.5 ± 3.1	11.3 ± 3.2	F = 135.85	<0.001
Chest-tube duration (days), mean ± SD	5.2 ± 1.9	4.5 ± 1.5	5.6 ± 1.8	6.9 ± 2.0	F = 181.04	<0.001
Pneumonia, n (%)	121 (9.5)	39 (5.4)	49 (14.6)	33 (15.7)	$\chi^2 = 33.50$	<0.001
Respiratory failure, n (%)	36 (2.8)	12 (1.7)	11 (3.3)	13 (6.2)	$\chi^2 = 12.41$	0.002
Unplanned ICU admission, n (%)	61 (4.8)	18 (2.5)	21 (6.3)	22 (10.5)	$\chi^2 = 24.71$	<0.001
Bronchoscopy for secretion clearance, n (%)	98 (7.7)	31 (4.3)	33 (9.8)	34 (16.2)	$\chi^2 = 35.09$	<0.001
30-day readmission, n (%)	56 (4.4)	24 (3.3)	20 (6.0)	12 (5.7)	$\chi^2 = 4.76$	0.093

ICU, intensive care unit; SD, standard deviation. Continuous variables were compared across the three risk groups using one-way analysis of variance, and categorical variables were compared using the chi-square test. The total-cohort column is descriptive and was not included as a separate group in the statistical comparisons.

more extensive dissection, or intraoperative complexity rather than duration itself [34]. It may also be associated with longer anesthesia exposure, greater fluid shifts, and increased postoperative respiratory suppression or pain [35,36,37]. Because operative time is known only during or after surgery, the full nomogram should not be described as a purely preoperative tool. The preoperative components of the model may help identify patients who need optimization before surgery, whereas the complete six-variable score is better suited to perioperative or early postoperative assessment. Operative time also remained significant as a continuous predictor. Restricted cubic spline analysis suggested modest nonlinearity, supporting the view that risk increased progressively rather than changing abruptly at exactly 180 minutes.

The nomogram is intentionally simple. All final predictors were entered as dichotomized variables; therefore, the resulting score is a weighted point system rather than a model that preserves the full continuous information of age, FEV1, operative time, or smoking exposure. Other prediction models developed for pulmonary complications after lung resection have similarly combined pulmonary-function and perioperative variables, although their predictors and target outcomes differ from those used in the present study [38]. This approach improves the applicability of the nomogram at the bedside but inevitably results in some loss of information. To examine the effect of this simplification, we constructed a sensitivity model using continuous forms of age, smoking exposure, FEV1, and operative time. The continuous-variable model showed only a small, non-significant improvement in AUC and demonstrated similar calibration performance, suggesting that dichotomisation did not materially alter overall model performance. More flexible modelling strategies, such as restricted cubic splines or penalized regression, may still improve predictive performance in future work. In the present study, we sought to ensure transparency in the modelling process by reporting the original candidate-variable framework, the number of variables entering the adjusted stage, and the events-per-variable values. Bootstrap validation suggested limited optimism in model performance, but external validation remains essential.

The risk categories also need to be interpreted as clinical groupings rather than biological cutoffs. The thresholds of <30%, 30%–60%, and >60% were fixed before comparing observed event rates. The 30% threshold was close to the Youden-derived cutoff, while the 60% threshold was chosen to separate a group with a clearly high predicted probability. The observed rates of 10.2%, 38.1%, and 79.0% across the three groups indicate good risk separation. In practice, these categories may help clinicians decide how closely to monitor postoperative imaging, how aggressively to support coughing and mobilization, and when to consider airway-clearance measures.

Patients in the higher-risk groups also had longer hospital stays and chest-tube durations and more frequent pneumonia, respiratory failure, ICU admission, and bronchoscopy. These findings indicate that risk-group membership was associated with a worse postoperative outcome. However, individual postoperative outcomes are interrelated and may reflect the same underlying delay in recovery; therefore, these comparisons should not be interpreted

as evidence of independent predictive value for each individual outcome.

The model should not be regarded as a substitute for clinical judgment; rather, it may serve as a structured reminder of several common but clinically meaningful risk factors. For example, a patient with COPD, reduced FEV1, heavy smoking history, and an upper lobectomy may require a more deliberate postoperative respiratory plan even if the operation itself is uncomplicated. Such a plan could include careful analgesia, early mobilization, incentive spirometry, chest physiotherapy, bronchodilator optimization, and timely assessment for secretion retention. For patients whose risk increases after prolonged procedures, escalation of postoperative monitoring may be warranted.

Several limitations should be considered. First, this was a retrospective single-center study. Local surgical technique, anesthesia practice, chest-tube management, imaging schedules, and discharge policies may all influence both the occurrence and detection of atelectasis. The model therefore needs validation in additional centers before routine clinical use. This is also consistent with current recommendations for clinical prediction models, which emphasize external validation before implementation [39,40].

Second, although the endpoint was assessed by thoracic radiologists, its definition remained dependent on radiographic interpretation and available imaging data. Patients discharged before postoperative day 7 were included only when post-discharge imaging was sufficient to determine whether atelectasis persisted or resolved. This approach reduced the risk of misclassification but may have also excluded some patients with short hospital stays. A prospective study with a fixed imaging schedule would provide a more robust assessment of this endpoint.

Third, some potentially relevant perioperative variables were not available in sufficient detail. These included intraoperative ventilatory settings, fluid balance, anesthetic regimen, longitudinal pain-control quality, cough strength, adherence to respiratory physiotherapy, and surgeon-level factors. These unmeasured variables may explain part of the residual risk and could be incorporated into future models.

Additionally, the model-development process involved screening a broad set of variables. Although 368 outcome events provided enough support for the final six predictors, the earlier candidate-selection stage was more complex. To reduce this problem, we reported the number of candidate predictors and degrees of freedom, reviewed variables by clinical domain, avoided unnecessary overlap where possible, assessed collinearity, and used bootstrap validation. Even so, some degree of selection-related optimism may remain. Future studies could further evaluate this nomogram against LASSO, ridge regression, or a fully prespecified modelling framework.

Notably, the present nomogram applies only to patients undergoing VATS lobectomy for NSCLC. It should not be assumed to perform similarly in patients undergoing wedge resection, segmentectomy, pneumonectomy, open thoracotomy, or surgery for metastatic disease. The study also excluded patients with severe baseline pulmonary dysfunction, so the findings may not be generalizable to the highest-risk surgical candidates.

Also, although continuous-variable and restricted cubic spline analyses reduced concern about arbitrary dichotomisation, the primary nomogram still uses binary predictors for ease of application. This inevitably results in some information loss, and a continuously specified model may be preferable if future external datasets demonstrate its added value.

Finally, this study evaluated risk prediction rather than the effects of intervention. A high predicted risk does not automatically identify the optimal preventive strategy. Whether nomogram-guided pulmonary care can reduce persistent atelectasis, shorten hospital stay, or decrease respiratory complications should be investigated prospectively [41,42].

Conclusion

In this VATS lobectomy cohort, persistent atelectasis was associated with older age, heavier smoking, COPD, reduced FEV1, upper-lobe resection, and longer operative time. The continuous-variable and restricted cubic spline analyses supported the direction of the primary findings and showed that the associations were not solely dependent on the selected cutoffs. The nomogram stratified patients into low-, intermediate-, and high-risk groups and demonstrated good performance in bootstrap validation. Because operative time is incorporated into the model, the complete risk score is intended for perioperative or early postoperative decision-making. Higher-risk groups were associated with a less favourable postoperative course, although these comparisons were descriptive rather than proof of independent prediction of each postoperative outcome. Validation in additional centres is required before the model can be considered for routine clinical use.

Availability of Data and Materials

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request and subject to institutional data sharing policies and patient privacy protections.

Author Contributions

KS: Conceptualization, Data curation, Formal analysis, Writing – original draft; XHD: Investigation, Methodology, Validation; ZHX: Resources, Visualization, Software; YY: Data collection, Formal analysis; RRZ: Supervision, Data interpretation; DLZ: Conceptualization, Project administration. All authors have been involved in revising

it critically for important intellectual content. All authors gave final approval of the version to be published. 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

This study was approved by the Ethics Committee of China Coast Guard Hospital of the Chinese People's Armed Police Force (Approval No. Wulun [2025] 0704; Acceptance No. 2507171611777). The study was conducted in accordance with the Declaration of Helsinki. Given the retrospective design and the use of de-identified clinical data, the requirement for written informed consent was waived by the ethics committee. Patient information was handled confidentially according to institutional privacy and data-protection requirements.

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Conflict of Interest

The authors declare no conflict of interest.

Declaration of Generative AI and AI-Assisted Technologies in Manuscript Preparation

During manuscript preparation, ChatGPT was used only for English language polishing and readability improvement. After its use, the authors thoroughly reviewed, verified, and revised all content to ensure accuracy and originality.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.24976/Discov.Med.202638211.208.

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