Article

To Study the Correlation Between the Anatomical Variation of Bronchial Vessels Identified by Preoperative Three-Dimensional CT Reconstruction and the Clinical Outcome After Complex Segmentectomy

Ann. Ital. Chir., 2026 97, 7: 1153–1161
https://doi.org/10.62713/aic.4552

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AIM: All enrolled patients with non-small cell lung cancer (NSCLC) undergoing complex pulmonary segmentectomy received standardized preoperative three-dimensional (3D) computed tomography (CT) reconstruction. This study aimed to classify bronchovascular anatomical variations identified on preoperative 3D CT reconstruction and to examine their associations with postoperative complications (POCs), exploratory technical surrogate measures, and short-term postoperative rehabilitation.
METHODS: From May 2022 to June 2025, a total of 170 patients with primary NSCLC who underwent thoracoscopic complex segmentectomy were included. All patients underwent preoperative thin-slice CT scanning and 3D reconstruction (Mimics 21.0). Anatomical variation patterns were identified by radiologists using a double-blind approach. Based on the presence of bronchovascular variations, patients were assigned to a variation group (n = 108) and a non-variation group (n = 62). POCs (defined as Clavien-Dindo grade II or higher), exploratory technical surrogate measures (minimum surgical margin distance and intersegmental plane integrity score), pathological indices (lymphatic invasion rate), and postoperative recovery parameters (pulmonary function and quality of life) were retrospectively extracted from medical records.
RESULTS: The overall incidence of POCs was significantly higher in the variation group compared with the non-variation group ($p < 0.05$), with a notable increase in persistent air leakage and pulmonary infections. For exploratory technical surrogate measures, the variation group showed a shorter minimum surgical margin distance, higher intersegmental plane integrity scores, and more frequent intraoperative plan adjustments (all $p < 0.05$). Pathological evaluation revealed a higher rate of lymphatic invasion in the variation group ($p < 0.05$), while no marked inter-group differences were observed in the number of positive lymph nodes ($p > 0.05$). In terms of postoperative recovery, patients in the variation group experienced a longer hospital stay, greater decline in 6-minute walking distance from baseline, and lower Short-Form 36 (SF-36) role-physical scores at 3 months postoperatively (all $p < 0.05$). All patients underwent standardized preoperative 3D CT reconstruction for anatomical assessment and surgical planning.
CONCLUSIONS: Bronchovascular anatomical variations identified through standardized preoperative 3D CT reconstruction were associated with higher rates of persistent air leakage (PAL), a higher rate of lymphatic invasion, pulmonary infection, less favorable exploratory technical surrogate measures, and delayed short-term postoperative functional recovery. Because all patients underwent 3D CT reconstruction, these findings should be interpreted as associations related to anatomical variation rather than evidence that 3D CT independently improves surgical decision-making or clinical outcomes.

Keywords: three-dimensional computed tomography; segmentectomy; bronchovascular anatomical variations; postoperative complications; technical surrogate measures

Introduction

Lung cancer (LC) remains one of the most prevalent and deadly malignant tumors worldwide. For early-stage non-small cell lung cancer (NSCLC), the standard surgical approach has progressively shifted from lobectomy to sublobar resection, particularly complex segmentectomy, to maximize preservation of healthy lung tissue and maintain postoperative pulmonary function [1]. However, a central challenge in complex pulmonary segmentectomy is the precise handling of bronchovascular anatomical variations. Approximately 30%–40% of patients exhibit bronchial branching abnormalities, such as accessory bronchi or common trunk bronchi, as well as vascular tortuosity, agenesis, or aberrant courses. Intraoperative misinterpretation of these variations may lead to severe complications, including massive hemorrhage, pulmonary atelectasis, or conversion to thoracotomy, thereby significantly increasing the risk of postoperative complications (POCs), includ-

Submitted: 19 January 2026 Revised: 28 March 2026 Accepted: 22 April 2026 Published: 14 July 2026
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Editor: Luca Bertolaccini

ing persistent air leakage (PAL) and pulmonary infections [2,3]. Accordingly, accurate preoperative identification of anatomical variations is essential to ensure surgical safety and optimize individualized surgical planning.

Currently, two-dimensional (2D) thin-slice computed tomography (CT) remains the mainstream modality for preoperative evaluation. However, its inherent limitations in spatial representation, together with overlapping image artifacts, may obscure subtle bronchovascular variations and lead to suboptimal preoperative assessment [4,5]. In contrast, three-dimensional computed tomography bronchography and angiography (3D-CTBA) has been increasingly adopted in clinical practice, as it enables intuitive visualization of the spatial relationships among segmental bronchi and pulmonary vessels. However, several key limitations persist in the existing literature. First, most studies emphasize technical feasibility or simple comparisons of perioperative outcomes between 3D and 2D imaging, while 3D reconstruction is often applied as a technical tool rather than a systematic framework for identifying variations and risk stratification [6,7]. Second, most existing reports are based on small sample sizes and lack a comprehensive analysis of the association between 3D-identified bronchovascular variations and clinically relevant outcomes, including POCs, surgical precision, and postoperative recovery [8,9]. Third, few studies have examined these effects within homogeneous cohorts managed by consistent surgical teams and standardized operative procedures, thereby limiting the robustness and generalizability of current evidence.

Based on these considerations, this retrospective cohort study included patients with NSCLC who underwent complex segmentectomy with standardized preoperative 3D CT reconstruction. The primary objectives of this study were as follows: (1) to systematically classify bronchovascular anatomical variations identified through preoperative 3D CT reconstruction; (2) to examine the unadjusted associations between these variations and POCs, exploratory technical surrogate measures, and postoperative recovery; and (3) to describe the potential clinical relevance of anatomical variation assessment in patients undergoing complex segmentectomy.

Methods

Research Design and Characteristics

This was a single-center retrospective cohort analysis that enrolled patients with primary NSCLC who underwent complex segmentectomy in the Department of Thoracic Surgery at Fuzhou Pulmonary Hospital between May 2022 and June 2025. Bronchovascular anatomical variations were identified using preoperative 3D CT reconstruction, and unadjusted inter-group differences in perioperative and postoperative outcomes were subsequently analyzed. The study protocol was approved by the Fuzhou Pulmonary Hospital ethics committee (No. 2023-010-02). Given the retrospective design, all data were extracted from the hospital electronic medical record system, and the requirement for informed consent was waived by the Fuzhou Pulmonary Hospital ethics committee. The research was conducted in accordance with the Declaration of Helsinki and applicable regulations for medical data protection, and all patient information was anonymized to ensure data confidentiality.

Subjects

The incidence of the primary endpoint, defined as Clavien-Dindo grade ≥ II POCs, was used to estimate sample size in G*Power 3.1 software (University of Dusseldorf, Düsseldorf, NRW, Germany). Based on previous retrospective studies of complex pulmonary segmentectomy [10], the expected POC rates were set at 28% in the variation group and 12% in the non-variation group, representing the midpoint of previously reported clinically relevant ranges. The calculation assumed a two-sided α of 0.05, statistical power of 80% (β = 0.2), and a 1:1.75 allocation ratio, reflecting the natural clinical distribution of bronchovascular variations. A continuity correction was applied to the two-proportion z-test, which was prespecified as the primary statistical method for the primary endpoint. Based on these assumptions, the minimum required sample sizes were 62 cases in the non-variation group and 108 cases in the variation group, which were fully satisfied by the final cohort of 170 patients.

Inclusion criteria were as follows: (1) pathologically confirmed primary NSCLC; (2) preoperative thin-slice CT scanning (slice thickness ≤1 mm) with 3D reconstruction (3D-CTBA); (3) thoracoscopic complex segmentectomy, defined as resection of two or more pulmonary segments or a single segmentectomy involving a complex intersegmental plane, such as basal or lingular segments; (4) surgery performed by the same experienced thoracic surgical team; (5) complete clinical data, including preoperative imaging, surgical records, and postoperative follow-up.

Exclusion criteria included: (1) metastatic NSCLC or benign pulmonary diseases; (2) poor-quality preoperative CT images, such as those affected by motion or metal artifacts, that precluded accurate reconstruction; (3) intraoperative conversion to thoracotomy or lobectomy; and (4) severe cardiopulmonary insufficiency [forced expiratory volume in one second (FEV_1)% <50%] or thoracic deformities. These criteria defined a selected cohort of patients with preserved baseline pulmonary function who completed thoracoscopic complex segmentectomy, and patients with severe cardiopulmonary impairment or intraoperative conversion to thoracotomy or lobectomy were not represented in the final analysis. Accordingly, the findings may not be directly generalizable to broader real-world populations undergoing lobectomy or converted procedures.

Participants were grouped according to preoperative 3D CT reconstruction findings into a variation group, defined by the presence of at least one bronchovascular anatomical variation [11], and a non-variation group, in which bronchial and vascular structures conformed to classical anatomical patterns. As a retrospective cohort, grouping followed natural clinical distribution. A total of 170 patients were included, comprising 108 cases in the variation group and 62 cases in the non-variation group, consistent with the approximate 60% prevalence of bronchovascular variation in clinical practice. Predefined equal allocation was not applied because grouping followed the natural distribution of bronchovascular anatomy in this retrospective cohort; however, this grouping strategy does not eliminate selection bias or ensure generalizability to all patients undergoing pulmonary resection.

Preoperative 3D CT Reconstruction and Variation Identification

All patients underwent chest CT, plain and contrast-enhanced, within one week of surgery, using standardized parameters (tube voltage 120 kV, automatic tube current adjustment, matrix 512 × 512). Imaging data were imported into Mimics 21.0 software (Materialise) for 3D reconstruction. Bronchial variations were classified according to established international bronchial anatomical classification systems, including accessory bronchi (supernumerary bronchi), common trunk bronchi, absent or additional branches (e.g., absent B3 bronchus or common trunk of B7 + 8), and tortuosity, defined as a segmental bronchial branching angle >90°.

Vascular variations were classified based on classical pulmonary arterial and venous anatomy, including aberrant branches (e.g., A7-derived V6c), common trunks involving two or more segmental vessels sharing a proximal origin, tortuous cross-segmental courses, and abnormal vessel caliber. Abnormal vessel caliber was defined as a diameter exceeding 30% of the mean value based on classical anatomical references, consistent with thresholds reported in previous 3D reconstruction-based vascular variation studies.

Surgical Methods

All thoracoscopic complex segmentectomies were performed by the same experienced thoracic surgical team. Each surgeon had experience with more than 500 cases of thoracoscopic pulmonary segmentectomy and had surpassed the procedural learning curve. This uniform surgical setting reduced inter-operator variability but may also have attenuated the measurable effect of anatomical variation, because experienced surgeons could compensate for complex bronchovascular anatomy through standardized exposure and dissection strategies. After induction of general anesthesia and double-lumen endotracheal intubation, patients were positioned in the contralateral decubitus position, with the ipsilateral upper limb elevated and secured, and the thorax appropriately elevated to widen the intercostal spaces. All procedures were performed using a standardized three-port thoracoscopic approach. Neither robot-assisted surgery nor single-port thoracoscopic techniques were employed. Specifically, a 1.5 cm observation port was created in the 7th intercostal space (ICS) along the anterior axillary line (AAL), a 3 cm main operating port was established in the 4th ICS at the AAL, and a 1.5 cm auxiliary port was placed in the 7th ICS at the scapular line.

Preoperative 3D CT reconstruction was used as an anatomical reference for reviewing the bronchial and vascular structures of the target lung segment before and during surgery. An ultrasonic scalpel was used to dissect the segmental bronchus and the corresponding vessels. The intersegmental plane was determined intraoperatively using the modified inflation-deflation method. After ligation of the target segmental bronchus, the operative lung was inflated with pure oxygen, followed by an approximately 15-minute interval to allow passive deflation of the preserved segments, thereby clearly delineating the inter-segmental boundary.

Parenchymal division was performed along this boundary using an electrocoagulation hook or ultrasonic scalpel, ensuring resection of the target lung segment while preserving intersegmental veins to the greatest extent possible. Upon completion of resection, fibrin sealant was uniformly applied to the intersegmental plane and the bronchial stump in all patients, and a 28 Fr thoracic drainage tube was positioned adjacent to the observation port. Postoperatively, all patients received standardized perioperative management protocols, including routine prophylactic antibiotic therapy (cefuroxime 1.5 g administered intravenously twice daily for 24 hours), standardized patient-controlled intravenous analgesia (PCA) with a uniform drug regimen, and consistent thoracic drainage management. Vital signs, drainage volume, and air leakage were monitored by trained nursing staff according to departmental standard protocols.

Endpoints

Primary Endpoint

The primary endpoint was the incidence of postoperative complications (POCs) of Clavien-Dindo grade II or higher within 30 days after surgery. These complications included persistent air leakage (PAL), pulmonary infections, pleural effusion requiring puncture and drainage, arrhythmia, and chylothorax.

Secondary Endpoints

(1) Exploratory technical surrogate measures: These measures were independently evaluated by two experienced thoracic radiologists who were blinded to patient grouping and clinical outcomes. Inter-observer consistency was evaluated using the intraclass correlation coefficient (ICC). The closest surgical margin distance was measured from postoperative pathological specimens. The intersegmental plane integrity score was evaluated using postoperative chest CT as follows: 1 point indicated a completely continuous intersegmental plane with intact intersegmental veins; 2 points indicated a partial defect <2 cm without a clear residual cavity; and 3 points indicated an obvious defect ≥2

cm with a residual ineffective cavity. Inter-observer consistency for this scoring system was excellent (ICC = 0.89, 95% CI 0.84–0.93). The ICC indicates inter-observer reproducibility but does not establish external validity of the scoring system. Additional exploratory indicators included the number of intraoperative plan adjustments, defined as documented changes in the planned dissection sequence, resection range, or intersegmental plane demarcation made during surgery in response to anatomical findings, as well as the preservation rate of key anatomical landmarks, including the segmental bronchial stump and intersegmental veins. This variable was retrospectively extracted from operative records and should be interpreted as a center-defined technical measure rather than a validated navigation endpoint. Postoperative chest CT was uniformly performed on postoperative day 3 for all patients to evaluate intersegmental plane integrity.

(2) Perioperative surgical outcomes: These included operative time, intraoperative blood loss, length of postoperative hospital stay, and the change in forced expiratory volume in one second (ΔFEV_1[%]) measured before surgery and 1 month postoperatively.

(3) Pathological indicators: These comprised the number of dissected lymph node stations (N1 + N2), the number of positive lymph nodes, pathological subtypes, and the rate of lymphatic vessel invasion as confirmed by postoperative histopathological examination.

(4) Postoperative rehabilitation indicators: These included Visual Analogue Scale (VAS) pain scores recorded on postoperative days 1, 3, and 7; results of the 6-minute walk test (6MWT) assessed preoperatively and at 1 month after surgery; and scores across all domains of the Short-Form 36 (SF-36) Health Survey evaluated at 3 months postoperatively [12,13]. The SF-36 domains included Physical Functioning (PF), Role-Physical (RP), Bodily Pain (BP), General Health (GH), Vitality (VT), Social Functioning (SF), Role-Emotional (RE), and Mental Health (MH).

Statistical Methods

Statistical analyses were performed using SPSS version 30.0 (IBM). Categorical variables are presented as numbers (percentage) [n (%)] and were compared using the chi-square test. For continuous variables, the Shapiro-Wilk test was first applied to assess normality. Normally distributed data were expressed as mean ± standard deviation ($\bar{x} \pm SD$), and comparisons were conducted using independent-sample t-tests or paired t-tests, as appropriate. Non-normally distributed data are presented as median (P25, P75) and were compared using the Mann-Whitney U test. For tables reporting 95% confidence intervals, the effect estimate was specified according to variable type. For continuous variables, the 95% confidence interval refers to the between-group mean difference. For categorical variables, the 95% confidence interval refers to the odds ratio (OR), unless otherwise stated.

For outcome variables measured repeatedly over time, including VAS pain scores (postoperative days 1, 3, and 7) and pulmonary function and 6MWT results (baseline and 1 month postoperatively), repeated measures analysis of variance (ANOVA) was used to evaluate the effects of between-subject factors (group: variation vs. non-variation), within-subject factors (time), and their interaction. Pairwise comparisons within groups across time points and between groups at the same time point were adjusted using the Bonferroni correction for multiple comparisons. A p-value < 0.05 was considered statistically significant. No multivariable regression, propensity-score matching, or inverse-probability weighting was performed. Therefore, the reported inter-group comparisons should be interpreted as unadjusted associations rather than independent effects or causal relationships.

Results

Inter-Group Comparison of Baseline Characteristics

The two groups were comparable in age, sex, body mass index (BMI), smoking history and other aspects (all $p >$ 0.05), suggesting no statistically significant differences in the measured baseline variables listed in Table 1. Analysis of bronchovascular anatomical variations showed that cases in the variation group were predominantly characterized by bronchial variations, followed by vascular variations, while combined variations were relatively uncommon. A single lesion was dominant. Because no multivariable adjustment, propensity-score method, or inverse-probability weighting was performed, all findings in the Results section should be read as unadjusted between-group comparisons, with no inference of independence, risk attribution, or causality.

Comparison of Exploratory Technical Surrogate Measures

In unadjusted comparisons, there was no difference in the number of completely transexuals between the two groups (p = 0.763); the variation group had a shorter closest surgical margin distance than the non-variation group; higher intersegmental plane integrity scores, more frequent intraoperative plan adjustments, and a different distribution of anatomical landmark preservation were also observed in the variation group (all $p < 0.05$, Table 2), but these exploratory surrogate measures should not be interpreted as validated direct measures of surgical precision.

Comparison of Surgical Outcomes

Compared with the non-variation group, the variation group demonstrated significantly longer operative time, greater intraoperative blood loss, and prolonged hospital stay ($p <$ 0.05). Within-group comparison of ΔFEV_1 indicated that the magnitude of pre- to postoperative decline was greater in the variation group than in the non-variation group ($p <$ 0.05, Table 3).

Table 1. Baseline characteristics of the study population.

Variables	Non-variation group (n = 62)	Variation group (n = 108)	Statistic (t/χ^2)	p-value
Age (years), mean ± SD	62.55 ± 9.28	61.57 ± 7.17	0.764	0.446
Sex, n (%)			0.779	0.377
Male	42 (67.74)	80 (74.07)		
Female	20 (32.26)	28 (25.93)		
BMI (kg/m^2), mean ± SD	23.77 ± 2.78	23.45 ± 3.15	0.672	0.503
Smoking status, n (%)	35 (56.45)	69 (63.89)	0.917	0.338
Tumor location, n (%)			0.803	0.669
Upper lobe	26 (41.94)	50 (46.30)		
Middle lobe	15 (24.19)	20 (18.52)		
Lower lobe	21 (33.87)	38 (35.19)		
TNM stage, n (%)			0.394	0.530
Stage I	42 (67.74)	68 (62.96)		
Stage II	20 (32.26)	40 (37.04)		
Preoperative FEV_1 (%), mean ± SD	84.43 ± 12.27	84.47 ± 11.73	0.021	0.983
Bronchovascular anatomical variations			-	-
Variation of bronchus	-	74 (68.52)		
Variation of blood vessels	-	31 (28.70)		
Combined variation	-	3 (2.78)		
Number of lesions			-	-
A single	-	84 (77.78)		
Multiple	-	24 (22.22)		\

BMI, body mass index; FEV_1, forced expiratory volume in one second; TNM, tumor node metastasis.

Table 2. Comparison of exploratory technical surrogate measures between groups.

Variables		Non-variation group (n = 62)	Variation group (n = 108)	Statistic ($t/U/\chi^2$)	Effect estimate (95% CI)	p-value
Tumor margin distance (mm), mean ± SD		22.91 ± 4.37	18.25 ± 6.53	5.011	–6.499– –2.826	<0.001
Intersegmental plane integrity score, mean ± SD		1.32 ± 0.47	1.77 ± 0.56	5.279	0.311–0.682	<0.001
Number of intraoperative plan adjustments, median (P25, P75)		1.00 (1.00, 3.00)	1.00 (0.00, 1.00)	4.767	–0.952– –0.394	<0.001
Preservation of anatomical landmarks (Bronchial stump), n (%)	Completely retained	30 (48.39)	33 (30.56)	5.369	1.116–4.128	0.021
	Partial injury	20 (32.26)	52 (48.15)	4.073	0.269–0.973	0.044
	Completely transected	12 (19.35)	23 (21.30)	0.091	0.399–1.882	0.763

Note: For continuous variables, the effect estimate is the mean difference between groups, calculated as the variation group minus the non-variation group. For categorical variables, the effect estimate is the unadjusted odds ratio (OR) for the listed category. These variables were analyzed as exploratory technical surrogate measures rather than validated direct measures of surgical precision.

Table 3. Comparison of perioperative surgical outcomes.

Groups	Non-variation group (n = 62)	Variation group (n = 108)	Statistic (t)	95% CI	p-value
Operative Time (minutes)	180.58 ± 30.11	213.31 ± 37.30	5.891	21.76–43.69	<0.001
Intraoperative Blood Loss (mL)	121.98 ± 42.67	140.82 ± 38.85	2.935	6.170–31.51	0.004
Length of Stay (days)	7.71 ± 1.05	9.04 ± 0.99	8.218	1.001–1.645	<0.001
ΔFEV_1 (%)	–6.27 ± 1.64	–7.94 ± 1.88	5.809	–2.225– –1.096	<0.001

ΔFEV_1, change in forced expiratory volume in one second.

Table 4. Comparison of postoperative pathological findings and lymph node dissection.

Groups		Non-variation group (n = 62)	Variation group (n = 108)	Statistic (t/χ^2)	95% CI	p-value
Dissected Lymph Node Stations (N1 + N2)		5.76 ± 0.95	5.16 ± 1.10	3.586	–0.931–0.270	<0.001
Total Number of Dissected Lymph Nodes		2.13 ± 0.98	1.95 ± 0.81	1.252	–0.452–0.101	0.212
Pathological Subtypes	Adenocarcinoma	46 (74.19)	74 (68.52)	1.564	-	0.457
	Squamous Cell Carcinoma	13 (20.97)	31 (28.70)			
	Others	3 (4.84)	3 (2.78)			
Lymphatic Vessel Invasion		11 (17.74)	35 (32.41)	4.292	0.202–0.963	0.038

Table 5. Comparison of POCs.

Groups	Non-variation group (n = 62)	Variation group (n = 108)	Statistic (χ^2)	95% CI	p-value
Persistent Air Leakage (>5 days), n (%)	4 (6.45)	19 (17.59)	4.179	0.115–0.916	0.041
Pulmonary Infection, n (%)	2 (3.23)	14 (12.96)	4.380	0.049–0.897	0.036
Pleural Effusion, n (%)	3 (4.84)	5 (4.63)	0.004	0.270–4.161	0.951
Arrhythmia, n (%)	1 (1.61)	1 (0.93)	0.160	0.091–33.60	0.689
Chylothorax, n (%)	1 (1.61)	0 (0.00)	1.752	-	0.186
Overall POC Incidence, n (%)	11 (17.74)	39 (36.11)	6.402	0.171–0.806	0.011

Note: Persistent air leakage was defined as continuous air leakage from the thoracic drainage tube for more than 5 consecutive days after surgery, requiring prolonged thoracic drainage or additional clinical intervention. The reported odds ratios and confidence intervals are unadjusted estimates. POC, postoperative complication.

Comparison of Postoperative Pathological Findings and Lymph Node Dissection Status

There were no significant differences between groups in the total number of dissected lymph nodes or pathological subtypes ($p > 0.05$). However, the variation group showed fewer dissected lymph node stations (N1 + N2) and a higher rate of lymphatic vessel invasion compared with the non-variation group ($p < 0.05$, Table 4).

Comparison of POCs

The overall incidence of POCs was 36.11% in the variation group, which was significantly higher than 17.74% observed in the non-variation group ($p < 0.05$). Further analysis showed no notable inter-group differences in the incidence of postoperative pleural effusion, arrhythmia, and chylothorax ($p > 0.05$). However, the variation group exhibited a higher incidence of persistent air leakage (PAL) lasting more than 5 days and pulmonary infections ($p < 0.05$, Table 5).

Comparison of Postoperative Rehabilitation

In terms of postoperative pain, VAS scores were comparable between groups on postoperative days 1 and 7 ($p > 0.05$), while the variation group had higher scores on postoperative day 3 ($p < 0.05$). In both groups, postoperative VAS scores decreased progressively over time ($p < 0.05$). Additionally, 6MWT values decreased after surgery in both groups. There was no significant difference between groups before surgery ($p > 0.05$). After operation, the test results of both groups decreased ($p < 0.05$). In terms of quality of life, the RP score of the non-variant group was lower than that of the variant group ($p < 0.05$). The RP dimension reflects limitations in daily activities due to physical health and represents a core marker of postoperative functional recovery in patients undergoing thoracic surgery (Fig. 1).

Discussion

The results of this study showed that, in unadjusted comparisons, the incidence of POC was higher in the variation group than in the non-variation group, particularly for PAL and pulmonary infections. In addition, the variation group showed less favorable exploratory technical surrogate measures, including shorter closest surgical margin distance and higher intersegmental plane integrity scores, together with extended hospital stay, greater decline in pulmonary function, and a higher lymphatic invasion rate. Taken together, these findings support the clinical relevance of documenting bronchovascular anatomical variations before complex segmentectomy, but they do not show that 3D CT reconstruction itself optimized surgical decision-making or reduced postoperative risks, because all enrolled patients received the same preoperative imaging strategy.

We further observed that bronchovascular anatomical variations identified by preoperative 3D CT reconstruction were associated, in unadjusted comparisons, with higher POC rates, less favorable exploratory technical surrogate measures, and delayed postoperative recovery. These findings can only be discussed as clinically plausible explanations, rather than confirmed mechanisms, because the present retrospective dataset was based on unadjusted inter-group comparisons: (1) Greater intraoperative technical complexity. Bronchial common trunk variations, the most frequent type in this cohort, are defined as two or more segmental bronchi sharing a single proximal trunk [14]. Even with

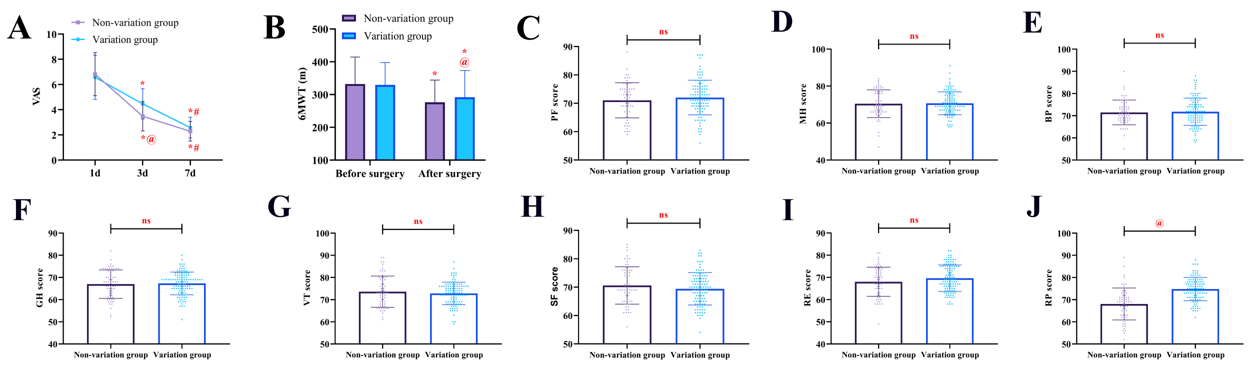

Fig. 1. Postoperative rehabilitation outcomes in the variation and non-variation groups. (A) Comparison of postoperative changes in Visual Analogue Scale (VAS) pain scores. *, #, and @ denote $p < 0.05$ compared with postoperative day 1, postoperative day 3, and the non-variation group, respectively. (B) Comparison of 6-minute walk test (6MWT) performance before and after surgery. * and # indicate $p < 0.05$ compared with the preoperative value and the non-variation group, respectively. (C–J) Comparison of quality-of-life scores assessed by the SF-36, including: (C) Physical Functioning (PF), (D) Mental Health (MH), (E) Bodily Pain (BP), (F) General Health (GH), (G) Vitality (VT), (H) Social Functioning (SF), (I) Role-Emotional (RE), and (J) Role-Physical (RP). ns indicates $p > 0.05$ and @ indicates $p < 0.05$ compared with the non-variation group.

standardized preoperative 3D reconstruction-based assessment, the complex spatial configuration of a common trunk may make intraoperative boundary identification more difficult; in this study, the higher number of intraoperative plan adjustments in the variation group is consistent with greater technical complexity, but it should not be taken as proof that anatomical variation independently caused operative injury or that 3D CT reduced decision errors. Abnormal vascular calibers have been proposed to affect local hemodynamics and surgical exposure [15], yet the present study did not directly measure these mechanisms, and the longer operative time in the variation group should therefore be interpreted as an unadjusted perioperative difference rather than a mechanistic consequence.

(2) Differences in exploratory intersegmental-plane measures. The intersegmental vein serves as a key anatomical landmark for defining the intersegmental plane, and venous variations (e.g., cross-segmental courses or aberrant branching patterns) may disrupt the conventional anatomical basis for plane identification [16]. Despite preoperative 3D mapping, intraoperative lung retraction and atelectasis can alter the spatial positioning of variant veins, thereby limiting the accuracy of intersegmental plane separation using the traditional inflation-deflation method. Higher intersegmental plane integrity scores may indicate a less favorable postoperative intersegmental-plane appearance, which could be clinically relevant to air leakage; however, because this scoring system has not been externally validated as a direct measure of surgical precision, the observed differences should be interpreted as exploratory technical findings rather than proof of reduced surgical precision. Similarly, the shorter margin distance and greater postoperative decline in pulmonary function observed in the variation group may reflect a more complex operative context, but these unadjusted comparisons cannot establish a causal pathway.

(3) Postoperative infection-related observations. The higher incidence of pulmonary infection in the variation group should be interpreted as an observed unadjusted difference; possible contributors include longer operative time, more difficult parenchymal division, residual ineffective cavities, or early PAL, but the present study was not designed to determine whether bronchovascular variations independently increased infection risk.

(4) Potential impact on tumor biological behavior and lymph node dissection. The higher rate of lymphatic vessel invasion in the variation group was an unadjusted pathological observation and should not be interpreted as evidence that anatomical variation promotes tumor invasiveness; although altered local hemodynamics or microenvironmental changes may be considered as hypotheses, the present study cannot evaluate these biological mechanisms. However, these findings are based on retrospective observations, and the underlying mechanisms require further validation through prospective studies with larger sample sizes.

In terms of postoperative pain, the higher VAS score observed on postoperative day 3 in the variation group may be attributed to prolonged operative time, more extensive intraoperative tissue dissection, poorer intersegmental plane integrity, and a higher incidence of postoperative PAL and pulmonary infection in this group. Collectively, these factors may aggravate the acute inflammatory response and contribute to increased chest pain during the early postoperative period. The comparable VAS scores on postoperative days 1 and 7 between the two groups may be explained by the standardized application of patient-controlled analgesia through the perioperative period, which likely mitigated intergroup differences in pain perception at these time points.

Regarding the difference in the number of dissected lymph node stations between the two groups, this finding may reflect greater technical difficulty of intraoperative lymph node exposure in the presence of bronchovascular anatomical variations; however, because the analysis was unadjusted and the operative records did not prospectively grade hilar exposure, this interpretation should be considered exploratory. Notably, no significant difference was observed in the number of positive lymph nodes between the two groups; this finding indicates only that no detectable intergroup difference was identified for this endpoint in the present cohort, and it does not establish that anatomical variation has no effect on staging accuracy. In addition, although altered local hemodynamics and tumor microenvironmental changes may be considered as hypotheses, the higher rate of lymphatic vessel invasion in the variation group should be interpreted only as an unadjusted pathological difference. However, this hypothesis warrants validation in mechanistic and prospective studies.

A previous study has questioned the clinical necessity of 3D CT reconstruction [17]. However, because every patient underwent standardized preoperative 3D CT reconstruction, the present findings should be interpreted as showing that patients with bronchovascular variations had a more challenging technical profile despite uniform anatomical assessment, rather than as evidence that 3D CT reconstruction reduced intrao perative uncertainty or prevented decision-making errors. Therefore, in the present study, preoperative 3D CT reconstruction should be regarded as a standardized anatomical assessment method rather than as a validated intervention that independently improves surgical decision-making or clinical outcomes. Prospective comparative studies are required to determine whether 3D CT-based planning provides incremental clinical benefit.

Several limitations of this study should be acknowledged. First, as a single-center retrospective study, all procedures were performed by the same experienced surgical team using standardized preoperative 3D CT planning and operative procedures. While this approach minimizes the confounding effect due to inter-operator variability, it may also attenuate the observable impact of anatomical variations on postoperative outcomes, as experienced surgeons may compensate for these variations through refined technical strategies. Because all procedures were performed by surgeons with similarly extensive experience, sensitivity analysis or stratification by surgeon experience was not feasible within this cohort. Therefore, external validation in multicenter cohorts with heterogeneous surgical expertise is necessary. In addition, the exclusion of patients converted to thoracotomy or lobectomy and those with poor baseline pulmonary function further narrows the applicability of the results. The present findings therefore should not be extrapolated to high-risk patients, technically failed thoracoscopic procedures, or routine lobectomy populations without caution. Second, selection bias may arise from the inclusion of only patients with complete follow-up data, and information bias cannot be excluded because some postoperative rehabilitation variables were extracted from electronic medical records. Third, although 3D CT reconstruction allowed classification of variation types, the severity or extent of these variations was not quantitatively graded. Future studies may benefit from integrating machine-learning-based approaches for automated variation characterization and prospective risk assessment. Finally, pulmonary function was assessed only at 1 month postoperatively, reflecting short-term recovery rather than long-term functional outcomes. Therefore, conclusions related to the long-term impact of anatomical variations on pulmonary function should be interpreted with caution, and further studies with extended follow-up are warranted.

Conclusions

Preoperative 3D CT reconstruction allowed standardized identification of bronchovascular anatomical variations in patients undergoing complex segmentectomy. In this selected single-center cohort, the presence of such variations was associated with higher rates of PAL and pulmonary infection, less favorable exploratory technical surrogate measures, including margin distance and intersegmental-plane integrity scores, and delayed short-term postoperative recovery; these exploratory measures should not be regarded as validated direct evidence of surgical precision. These findings should not be interpreted as evidence that 3D CT reconstruction independently improves surgical decision-making, because all patients underwent the same preoperative imaging strategy and no adjusted or comparative analysis of 3D CT use was performed. Further multi-center prospective studies with broader patient populations, longer follow-up, and prespecified subgroup analyses are required to confirm the generalizability and clinical utility of these observations.

Availability of Data and Materials

All data included in this study can be obtained by contacting the corresponding author if needed.

Author Contributions

CHM conceived and designed the research, collected, analyzed the data and drafted the manuscript. JGP collected the data. NL contributed to the study design and data analysis. All authors contributed to the critical revision of the manuscript for important intellectual content. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

The study protocol was approved by the Fuzhou Pulmonary Hospital ethics committee (No. 2023-010-02). Given the retrospective design, all data were extracted from the hospital electronic medical record system, and the requirement for informed consent was waived. The research was conducted in accordance with the Declaration of Helsinki and applicable regulations for medical data protection, and all patient information was anonymized to ensure data confidentiality.

Acknowledgment

Not applicable.

Funding

This research received no external funding.

Conflict of Interest

The authors declare no conflict of interest.

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