Original Article

Quantitative computed tomography assessment of pulmonary function and compensation after lobectomy and segmentectomy in lung cancer patients

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Background: The effect of different surgical methods on postoperative lung function in patients with lung cancer is still inconclusive. The main objective of this study was to compare the effects of video-assisted thoracic surgery (VATS) lobectomy and segmentectomy on postoperative pulmonary function and compensatory changes in patients undergoing lung cancer surgery.

Methods: A total of 120 patients (82 VATS lobectomy, 38 VATS segmentectomy) were assessed for demographic characteristics, baseline pulmonary function, tumor volume, T stage, and histological grade. Postoperative pulmonary function and compensatory changes [percentage of the well-aerated lung (WAL) total (or unilateral) lung volume (LV) (WAL%) and non-operated lung (NOL)] were measured at multiple time points up to 2 years. Logistic regression analysis identified factors associated with WAL% decline after 1 year.

Results: Both VATS lobectomy and segmentectomy led to a decrease in pulmonary function, with no significant difference in the extent of decline between the two groups (all P>0.05). Lobectomy triggered a more pronounced compensatory response, characterized by increased ipsilateral NOL volume over time. Segmentectomy induced minimal compensatory changes and had a minimal impact on pulmonary function. Factors associated with decreased pulmonary ventilation after 1 year differed between the lobectomy and segmentectomy groups. In the lobectomy group, a higher preoperative WAL% of ipsilateral NOL [odds ratio (OR) =1.073; 95% confidence interval (CI): 1.017–1.133; P=0.01] was associated with a higher risk of decline in pulmonary function, whereas in the segmentectomy group, the only influencing factor was the preoperative contralateral mean lung density (MLD) (OR =0.932; 95% CI: 0.884–0.984; P=0.01).

Conclusions: Both lobectomy and segmentectomy after lung cancer surgery result in a decrease in WAL%, with lobectomy demonstrating a stronger pulmonary compensatory capacity. The application of quantitative computed tomography (CT) has shown significant value in predicting postoperative pulmonary function preservation and compensatory changes, providing strong support for personalized surgical decision-making.

Keywords: Video-assisted thoracic surgery lobectomy (VATS lobectomy); VATS segmentectomy; postoperative pulmonary function; compensatory changes; lung cancer surgery

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Introduction

Lung cancer is currently the second commonest malignancy worldwide, posing a significant threat to human health and life (1,2). For a long time, the National Comprehensive Cancer Network Guidelines have recommended anatomical lung lobe resection combined with systematic lymph node dissection as the standard surgical approach for curative treatment of early-stage non-small cell lung cancer. With the widespread application of low-dose computed tomography (CT) for lung cancer screening, the detection rate of early-stage lung cancer has substantially increased, leading researchers to examine the feasibility of sublobar resection (3).

Recent evidence suggests intentional segmentectomy may be considered in certain situations, e.g., unfeasible lobectomy and peripheral small nodules meeting specific criteria (4-6). Despite the above recommendations, the clinical application of segmentectomy for lung cancer remains significantly limited. Although studies comparing lobectomy and segmentectomy have reported similar survival, tumor recurrence, and complication rates, there are conflicting findings about postoperative pulmonary function preservation between these two procedures (7-9). Some research indicates no significant difference in lung function outcomes, while others suggest segmentectomy may better preserve pulmonary function post-surgery.

Currently, several clinical studies are assessing overall pulmonary function following curative lung cancer surgery by utilizing forced expiratory volume in 1 second (FEV_1) and forced vital capacity (FVC) from pulmonary function tests (PFTs), which calculate the percentage change in pulmonary function before and after surgery to determine the disparity in preserving pulmonary function between lobectomy and segmentectomy in postoperative patients (10-13). However, PFTs indirectly evaluate overall pulmonary function through gas flow measurements but with limited accuracy. Moreover, the results of PFTs heavily rely on patient cooperation, and some lung cancer patients may not tolerate the test. Recent advancements in CT image post-processing techniques have enabled quantitative assessment of pulmonary function. Unlike PFTs, quantitative CT analysis directly measures lung tissue and provides objective quantitative indicators such as lung volume (LV) and density. Quantitative CT analysis facilitates rapid lesion localization and enables evaluation of pulmonary function based on the entire lung, a single lung lobe, or one side of the lung using automated segmentation of lung lobes and threshold analysis. Notably, quantitative CT analysis has demonstrated clinical value across various conditions including emphysema, chronic obstructive pulmonary disease, and lung cancer (14-16). Furthermore, a recent study demonstrated that a deep learning model applied to volumetric chest CT scans can predict pulmonary function with relatively high accuracy (17). However, there is a scarcity of studies that investigate quantitative CT assessment of pulmonary function specifically related to lung cancer.

Highlight box

Key findings

- The study underscores the decline in well-aerated lung (WAL) volume [percentage of the WAL to total (or unilateral) lung volume] post-lung cancer surgery with both lobectomy and segmentectomy, emphasizing enhanced compensatory lung capacity in patients with lobectomy. Crucially, it showcases the significant value of quantitative computed tomography (CT) in predicting postoperative pulmonary function and compensation of patients with lung cancer.

What is known and what is new?

- Existing studies have provided different insights into the effects of lobectomy and pulmonary segmentectomy on postoperative lung function in patients with lung cancer.
- This research highlights the finding of a more pronounced compensatory response in pulmonary function following lobectomy compared to segmentectomy. Importantly, it evidences the utility of quantitative CT evaluations in predicting pulmonary function and compensatory changes after surgery.

What is the implication, and what should change now?

- This study highlights the clinical value of quantitative CT in assessing pulmonary function and its compensatory changes following lung cancer surgery, presenting an essential resource for the clinical monitoring of lung function recovery. By enabling the straightforward evaluation and prediction of postoperative pulmonary function in patients following various surgical methods, it provides a reference for determining the optimal surgical strategy.

Therefore, the primary objective of this study was to leverage the precision and depth of quantitative CT to thoroughly assess and compare the postoperative pulmonary function and compensatory LV changes in patients undergoing lobectomy and segmentectomy for lung cancer treatment. By quantifying the well-aerated lung (WAL) and non-operated lung (NOL) tissue, this research aims to provide a clearer, objective evaluation of lung function preservation and adaptation after these surgical interventions. Understanding these dynamics is critical for tailoring surgical approaches to individual patient needs, potentially guiding more personalized, function-preserving cancer treatments. This study's findings could significantly impact clinical practice by informing surgeons of the potential functional outcomes of each surgical method, thereby facilitating more informed decision-making that optimizes both oncological control and post-surgical pulmonary function. We present this article in accordance with the STROBE reporting checklist (available at https://jtd.amegroups.com/article/view/10.21037/jtd-24-492/rc).

Methods

Patients

Patients with lung cancer administered for radical surgery in the Union Hospital of Tongji Medical College from June 2020 to September 2021 were enrolled. This retrospective, single-center study was approved by the Ethics Committee of Wuhan Union Hospital, Wuhan, China (No. 0526), which waived the requirement for informed consent due to the retrospective nature of the study. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013).

Inclusion criteria were: diagnosis of lung cancer and thoracoscopic resection of a single lung lobe or lung segment in Wuhan Union Hospital; PFT and CT examinations before surgery, and follow-up CT after surgery (at 3 months, 6 months, 1 year, 2 years postoperatively). Exclusion criteria were: a history of tumor, a history of chronic pulmonary disease, a history of thoracic surgery, thoracic malformation, chemoradiotherapy, and distant metastasis. Pathological type, T-stage, postoperative complications, and baseline data for all patients were collected through the electronic medical record system, including age, gender, height, weight, previous disease history (hypertension and diabetes), smoking history, etc.

Chest CT scanning protocol and image post-processing

All chest CT examinations were performed with a Philips Ingenuity Core128 CT scanner (Philips Medical Systems, Best, Netherlands). Prior to scanning, patients were trained on breath control, and images were obtained during breath-holding at full inspiration. The tube voltage was set at 120 kVp with adaptive current modulation, resulting in a volume CT dose index (CTDIvol) of 7.1±2.2 mGy (range, 3.1–12.2 mGy) and a dose length product (DLP) of 286.0±97.2 mGy·cm (range, 99.2–506.3 mGy·cm). Other acquisition parameters were: pitch, 0.999; collimation, 64 mm × 0.625 mm; gantry rotation time, 0.75 s; DoseRight index, 18. Axial CT images were reconstructed from raw data by iterative reconstruction (iDose level 5, Philips Healthcare, Best, Netherlands) with a matrix size of 512×512 (a thickness of 1.5 mm and an increment of 1.5 mm), using a pulmonary B70f kernel and a mediastinal B30f kernel.

The Pulmo 3D Workspace of Syngo Via was employed for quantitative analysis of lung and lobar volume, following established protocols. Automatic segmentation of each lobe was achieved by identifying the contours of bilateral lungs and interlobular fissures (left oblique and right horizontal and oblique fissures). The lungs were meticulously segmented, excluding soft tissues, large vessels, atelectasis, fibrosis, lung tumors, and hyperinflated areas, with threshold limits set from −950 to −700 Hounsfield unit (HU). This precise segmentation yielded the radiologically defined volume of WAL tissue (18-20). Various parameters of interest were examined using the latter approach, including (I) mean lung density (MLD) of total lung (HU); (II) total (or unilateral) LV (cm^3); (III) percentage of unilateral lung to total LV (LV%); (IV) WAL tissue volume (cm^3); (V) percentage of the WAL to total (or unilateral) LV (WAL%); (VI) the emphysema index (EI) was defined as the percentage area of lung with attenuation values below −950 HU; and (VII) total (or ipsilateral) NOL (cm^3) (11). Ipsilateral NOL stands for the lung tissue retained on the affected side after surgery.

PFTs

All PFTs were performed by two experienced technicians with the Master Lab equipment (CareFusion, Hoechberg, Germany) following the American Thoracic Society standards preoperatively. The following indexes were

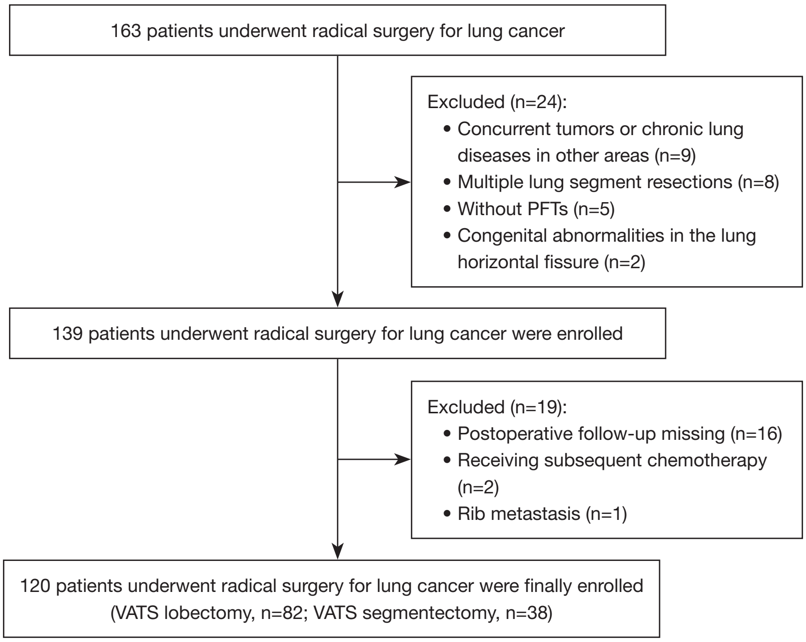

Figure 1 Flowchart of the patient's inclusion and exclusion process. PFT, pulmonary function test; VATS, video-assisted thoracic surgery.

recorded: FEV_1, FVC, FEV_1/FVC ratio, maximal instantaneous forced expiratory flow where 75% and 50% of the FVC remains to be expired [maximal expiratory flow (MEF)75% and MEF50%, respectively] and maximum mid-expiratory flow (MMEF). All results were expressed as a percentage of the predicted value.

Statistical analysis

IBM SPSS Statistics Software (version 26; IBM, New York, NY, USA) was utilized for data analysis. Categorical variables were presented as number (%), and continuous variables as median (Q1, Q3). The patients were divided into the lobectomy and segmentectomy groups according to surgical method. Demographic characteristics, data from PFTs, tumor location, tumor size, T stage, histologic diagnosis, and quantitative CT indexes were compared between the two groups. Categorical variables were compared by the chi-square test or the Fisher's exact test, and continuous variables by the Mann-Whitney *U* test. Stepwise logistic regression was used to determine the associations of potential predictors with the occurrence of WAL% decrease. Independent variables included sex, age, body mass index (BMI), smoking history, tumor location, preoperative ventilatory function, and preoperative CT quantitative indexes, i.e., MLD, LV%, and WAL% of the operated lung lobe; MLD, LV%, and WAL% of the contralateral side; and total NOL, ipsilateral NOL and WAL% of ipsilateral NOL. Indicators with P<0.05 were included in multivariate analysis. Statistical significance was considered at two-tailed P<0.05.

Results

Basic characteristics

Totally 163 patients underwent radical surgery for lung cancer, among whom 43 were excluded, including 16 cases with missing postoperative follow-up data, nine with concurrent tumors or chronic lung diseases in other areas, eight with multiple lung segment resections, five without PFTs, two administered subsequent chemotherapy, two with congenital abnormalities in the lung horizontal fissure, and one with rib metastasis. Finally, 120 patients were analyzed in the current study, including 82 cases administered video-assisted thoracic surgery (VATS) lobectomy and 38 administered VATS segmentectomy. The flowchart of patient enrollment is depicted in *Figure 1*. Except for age that was elevated in the lobectomy group compared with the segmentectomy group (P=0.005), other demographic characteristics were well balanced between the two groups. No differences were detected in baseline pulmonary function indexes between the two groups (all P>0.05).

Compared with the lobectomy group, the segmentectomy group had smaller tumor volume (P<0.001), earlier T stage (P=0.005), and lower histological grade (P<0.001) (*Table 1*).

Postoperative pulmonary function and compensatory changes in the two groups

As observed *Table 2*, WAL% decreased in both groups after surgery, but there was no difference in the proportion of individuals with WAL% decline in each period (all P>0.05). At 2 postoperative years, more than half of all patients in both groups had WAL% decline *vs.* preoperative values [lobectomy group, 19/36 (52.78%); segmentectomy group, 7/10 (70.00%)].

There were no differences in lung compensation indexes (increased NOL, increased ipsilateral NOL) between the two groups at 1 month after surgery (all P>0.05). At 3 months after surgery, higher numbers of patients had increased NOL in the total lung and the operative side in the lobectomy group compared with the segmentectomy group [total NOL: 44/59 (74.58%) *vs.* 16/31 (51.61%), P=0.03; ipsilateral NOL: 43/59 (72.88%) *vs.* 13/31 (41.94%), P=0.004]. At 6 months postoperatively, there was no statistically difference in the proportion of patients with increased total NOL volume between the two groups (P=0.24), but the lobectomy group still had a higher number of patients with increased ipsilateral NOL volume compared with the segmentectomy group [50/62 (80.65%) *vs.* 11/25 (44.00%), P=0.001]. Similar to 6-month follow-up CT data, at 1 year after surgery, there a higher number of patients had an increase in ipsilateral NOL volume in the lobectomy group compared with the segmentectomy group [58/67 (86.57%) *vs.* 14/28 (50.00%), P<0.001]. By 2 years after surgery, no difference was found in the proportion of patients with increased NOL volume between the two groups (P>0.05).

Preoperative and 1-year follow-up CT quantitative indexes

As shown in *Figure 2*, patients in the lobectomy group had significant increases in NOL volume, ipsilateral NOL volume, and the WAL of ipsilateral NOL at 1 year postoperatively (all P<0.05), while the segmentectomy group showed no differences in these indexes in this time period. The ratios of contralateral LV to total LV were significantly increased in both groups at 1 year postoperatively [lobectomy group, 55.79 (51.58, 62.10) *vs.* 47.32 (45.46, 53.67), P<0.001; segmentectomy group, 55.90 (50.45, 59.56) *vs.* 49.13 (45.81, 53.63), P<0.001]. However, the ratios of contralateral WAL volume to total LV were decreased in the lobectomy group at 1 year postoperatively [77.23 (62.4, 85.27) *vs.* 82.60 (76.64, 86.20), P=0.008]. There was no statistical difference in EI between the two groups of patients 1 year after surgery compared to preoperative levels (*Table 3*).

Factors associated with WAL% decline 1 year after surgery

A stepwise logistic regression analysis was performed to determine predictors of WAL% decline 1 year after surgery (*Table 4*). The findings revealed that in the lung lobectomy group, higher preoperative WAL% of ipsilateral NOL was linked to a higher risk of WAL% decline in lung ventilation at 1 year after surgery [odds ratio (OR) =1.073; 95% confidence interval (CI): 1.017–1.133; P=0.01]. In the lung segmentectomy group, the only influencing factor of WAL% decline 1 year after surgery was preoperative contralateral MLD (OR =0.932; 95% CI: 0.884–0.984; P=0.01).

Sequential CT follow-up data at 3 months, 6 months, and 1 year postoperatively

In the 57 lung cancer patients with CT follow-up data at 3 months, 6 months, and 1 year after surgery, continuous changes in CT quantitative indexes are shown in *Table 5* and *Figure 3*. In the lobectomy group, total NOL volume gradually increased after surgery and was stabilized at 6 months postoperatively, while ipsilateral NOL volume increased with longer postoperative time. The segmentectomy group showed no statistically differences in NOL volume compared with preoperative values (all P>0.05). In the lobectomy group, whole-lung WAL% gradually increased within 6 months after surgery (3 months postoperatively, 76.72; 6 months postoperatively, 79.15), while recovery rate decreased from 6 months to 1 year (6 months postoperatively, 79.15; 1 year postoperatively, 80.97). Statistical analysis showed that WAL% at 1 year postoperatively was consistent with preoperative value (P=0.14). In the segmentectomy group, there were no differences in WAL% between postoperative and preoperative values (all P>0.05). Additionally, it can be observed that the EI of NOL in the segmentectomy group gradually decreased after surgery.

Table 1 Clinical characteristics in patients receiving VATS lobectomy and VATS segmentectomy

Variables	Lobectomy group (n=82)	Segmentectomy group (n=38)	P value
Sex			0.14
Male	33 (40.24)	10 (26.32)	
Female	49 (59.76)	28 (73.68)	
Age (years)	58 [54, 64]	52 [44, 58]	0.005
BMI (kg/m^2)	22.9854 [21.5139, 25.1039]	22.68 [21.4844, 24.3032]	0.32
Smoking history	16 (19.51)	7 (18.42)	0.89
Comorbidities			0.69
Hypertension	20 (24.39)	8 (21.05)	
Diabetes	7 (8.54)	3 (7.89)	
Baseline pulmonary function			
FEV_1/FVC (%)	89.75 [84.6, 93.8]	89.4 [83.4, 95.1]	0.90
FEV_1 (% of pred)	106.5 [93.9, 115.6]	102.2 [94, 112]	0.61
MEF75% (% of pred)	95.4 [73, 112.7]	101.5 [85, 113]	0.34
MEF50% (% of pred)	66.3 [54.8, 91.2]	72.9 [54.6, 85]	0.91
MMEF (% of pred)	59.45 [45.1, 82.4]	62 [47.4, 78.8]	0.71
FVC (% of pred)	116.1 [106.4, 126.8]	118 [105.3, 126.1]	0.90
Location of tumor			0.76
Left upper lobe	14 (17.07)	10 (26.32)	
Left lower lobe	15 (18.29)	6 (15.79)	
Right upper lobe	34 (41.46)	14 (36.84)	
Right middle lobe	4 (4.88)	0 (0.00)	
Right lower lobe	15 (18.29)	8 (21.05)	
Tumor size (cm)	2 [1, 2.3]	1 [0.8, 1.2]	<0.001
T stage			0.005
Tis	1 (1.22)	10 (26.32)	
T1mi	5 (6.10)	18 (47.37)	
T1a	21 (25.61)	4 (10.53)	
T1b	35 (42.68)	5 (13.16)	
T1c	15 (18.29)	1 (2.63)	
T2a	4 (4.88)	0 (0.00)	
T2b	1 (1.22)	0 (0.00)	
Histologic diagnosis			<0.001
AIS	1 (1.22)	10 (26.32)	
MIA	5 (6.10)	18 (47.37)	
Invasive non-mucinous lung adenocarcinoma	71 (86.59)	9 (23.68)	
Invasive mucinous lung adenocarcinoma	1 (1.22)	0 (0.00)	
Squamous cell carcinoma	4 (4.88)	1 (2.63)	

Data are presented as n (%) or median [Q1, Q3]. P values comparing with group 1 and group 2 are from χ^2 test, Fisher's exact test or Mann-Whitney *U* test. VATS, video-assisted thoracic surgery; BMI, body mass index; FEV_1, forced expiratory volume in 1 second; FVC, forced vital capacity; MEF, maximal expiratory flow; MMEF, maximum mid-expiratory flow; AIS, adenocarcinoma in situ; MIA, minimally invasive adenocarcinoma.

Table 2 Comparison of postoperative pulmonary function and compensatory changes between the two groups

Variables	Lobectomy group	Segmentectomy group	P value
1-month follow-up CT (n=18)			
Time from surgery to follow-up onset (days)	38.5 [33, 41.5]	35.5 [33, 38]	0.55
Increased NOL	7/16 (43.75)	0/2 (0.00)	0.23
Increased ipsilateral NOL	5/16 (31.25)	0/2 (0.00)	0.35
Decreased WAL%	13/16 (81.25)	2/2 (100.00)	0.50
3-month follow-up CT (n=90)			
Time from surgery to follow-up onset (days)	97 [87, 105.5]	96.5 [91, 113]	0.35
Increased NOL	44/59 (74.58)	16/31 (51.61)	0.03
Increased ipsilateral NOL	43/59 (72.88)	13/31 (41.94)	0.004
Decreased WAL%	48/59 (81.36)	23/31 (74.19)	0.43
6-month follow-up CT (n=87)			
Time from surgery to follow-up onset (days)	199 [178, 244]	204 [182, 225]	0.84
Increased NOL	43/62 (69.35)	14/25 (56.00)	0.24
Increased ipsilateral NOL	50/62 (80.65)	11/25 (44.00)	0.001
Decreased WAL%	39/62 (62.90)	16/25 (64.00)	0.92
1-year follow-up CT (n=95)			
Time from surgery to follow-up onset (days)	391 [352, 423]	362 [349.5, 382.5]	0.11
Increased NOL	48/67 (71.64)	17/28 (60.71)	0.30
Increased ipsilateral NOL	58/67 (86.57)	14/28 (50.00)	<0.001
Decreased WAL%	39/67 (58.21)	20/28 (71.43)	0.23
2-year follow-up CT (n=46)			
Time from surgery to follow-up onset (days)	625 [577, 711.5]	551.5 [538, 683]	0.11
Increased NOL	27/36 (75.00)	7/10 (70.00)	0.75
Increased ipsilateral NOL	31/36 (86.11)	7/10 (70.00)	0.23
Decreased WAL%	19/36 (52.78)	7/10 (70.00)	0.33

Data are presented as median [Q1, Q3] or n/N (%). P values comparing with group 1 and group 2 are from χ^2 test, Fisher's exact test or Mann-Whitney *U* test. CT, computed tomography; NOL, non-operated lung; WAL%, percentage of the WAL to total (or unilateral) LV; WAL, well-aerated lung; LV, lung volume.

Discussion

This research assessed the impact of VATS lobectomy *vs.* segmentectomy on postoperative lung function and compensatory lung changes, revealing that patients from both groups experienced a decrease in WAL volume. Notably, the lobectomy group showed a more marked increase in NOL volume, indicating a stronger compensatory response, primarily attributed to the adaptation capabilities of the remaining lung tissue. Furthermore, the decline in WAL% at 1 year postoperatively was closely related to the preoperative MLD of the contralateral NOL and WAL% of the ipsilateral NOL, highlighting the role of quantitative CT in predicting postoperative lung function changes.

WAL, determined via CT image analysis, refers to the volume of WAL tissue and typically includes lung

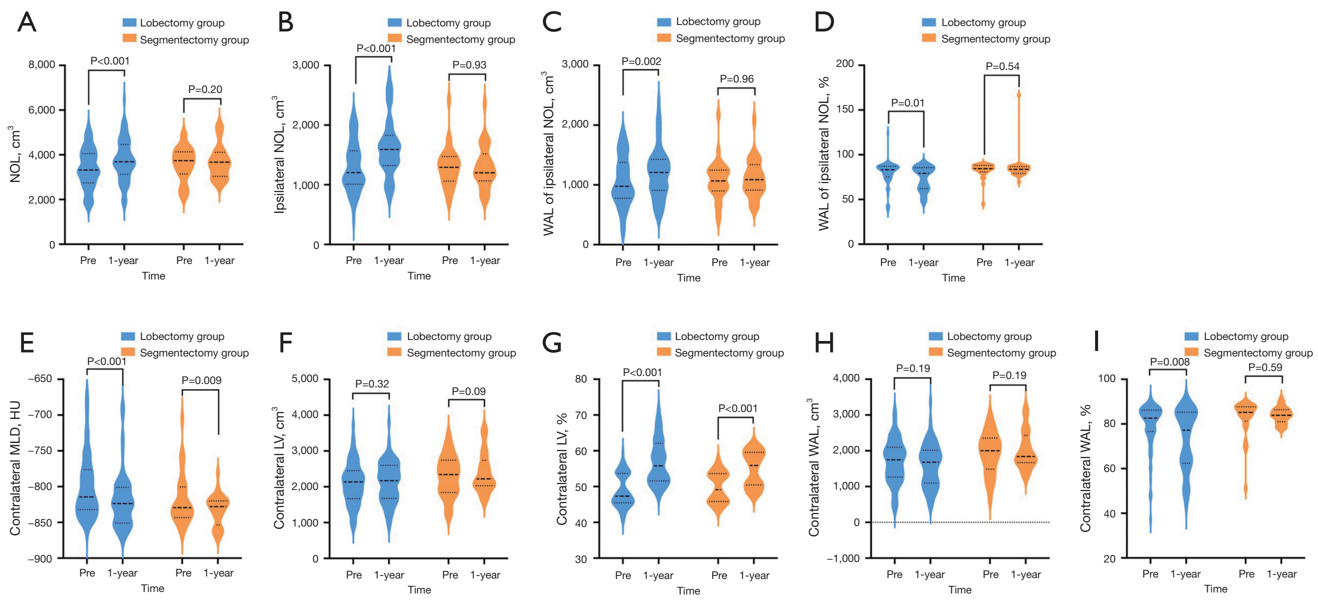

Figure 2 Comparison of preoperative and 1-year follow-up CT quantitative indexes. NOL, non-operated lung; pre, pre-operation; WAL, well-aerated lung; WAL%, percentage of the WAL to total (or unilateral) LV; LV, lung volume; MLD, mean lung density; HU, Hounsfield unit; LV%, percentage of unilateral lung to total LV; CT, computed tomography.

Table 3 Comparison of preoperative and 1-year follow-up CT quantitative indexes

Variables	Lobectomy group			Segmentectomy group		
	Pre-operation	1 year follow-up CT	P value	Pre-operation	1 year follow-up CT	P value
NOL (cm^3)	3,319.7 (2,741.8, 4,053.7)	3,686 (3,127, 4,463.1)	<0.001	3,737.45 (3,138.875, 4,132.45)	3,667.6 (3,035.85, 4,109.45)	0.20
Ipsilateral NOL (cm^3)	1,204.8 (1,009.1, 1,570.3)	1,591.7 (1,321.7, 1,829)	<0.001	1,293.1 (1,062.375, 1,473.75)	1,201.45 (1,067.025, 1,518.275)	0.93
WAL of ipsilateral NOL	974.7 (776.3, 1,374.1)	1,206.7 (906.57, 1,425.9)	0.002	1,066.1 (898.575, 1,247.9)	1,087.75 (912.675, 1,338.225)	0.96
WAL% of ipsilateral NOL	83.27 (75.51, 86.72)	79.24 (62.65, 85.28)	0.01	84.42 (80.88, 88.00)	83.66 (79.06, 86.76)	0.54
Contralateral MLD (HU)	−814.5 (−832.2, −776.3)	−823.6 (−851, −801)	<0.001	−829.35 (−843.35, −800.4)	−827.9 (−853.525, −820)	0.009
Contralateral LV (cm^3)	2,133.8 (1,668.7, 2,449.6)	2,170 (1,676.2, 2,600.1)	0.32	2,340.9 (1,839.25, 2,743.75)	2,222.1 (2,027.6, 2,737.9)	0.09
Contralateral LV%	47.32 (45.46, 53.67)	55.79 (51.58, 62.10)	<0.001	49.13 (45.81, 53.63)	55.90 (50.45, 59.56)	<0.001
Contralateral WAL (cm^3)	1,745.7 (1,268.1, 2,098.2)	1,679.2 (1,098.02, 2,016.7)	0.19	1,999.2 (1,483.375, 2,354.25)	1,838.7 (1,668.1, 2,430.925)	0.19
Contralateral WAL%	82.60 (76.64, 86.20)	77.23 (62.4, 85.27)	0.008	85.2032 (81.312, 87.688)	83.9034 (81.0138, 86.3723)	0.59
EI	0.82 (0.25, 2.37)	0.96 (0.32, 2.55)	0.13	0.64 (0.37, 1.98)	0.60 (0.23, 1.77)	0.09

Data are presented as median (Q1, Q3). P values comparing with pre-operation and 1 year follow-up CT are from Mann-Whitney *U* test. CT, computed tomography; NOL, non-operated lung; WAL, well-aerated lung; WAL%, percentage of the WAL to total (or unilateral) LV; LV, lung volume; MLD, mean lung density; HU, Hounsfield unit; LV%, percentage of unilateral lung to total LV; EI, emphysema index.

Table 4 Logistic regression analysis predicting decreased WAL% after 1 year after surgery

Variables	Coefficient	OR (95% CI)	P value
Lobectomy group			
WAL% of ipsilateral NOL	0.071	1.073 (1.017, 1.133)	0.01
Segmentectomy group			
Contralateral MLD	−0.070	0.932 (0.884, 0.984)	0.01

WAL%, percentage of the WAL to total (or unilateral) LV; WAL, well-aerated lung; LV, lung volume; OR, odds ratio; CI, confidence interval; NOL, non-operated lung; MLD, mean lung density.

tissue with densities ranging from −950 to −700 HU. This parameter serves as a crucial quantitative indicator for assessing pulmonary function by reflecting the amount of lung tissue with normal function and ventilation capacity. Our findings demonstrate that although both lobectomy and segmentectomy groups showed a decline in WAL% within 2 years postoperatively, no difference was observed between the two groups. These insights suggest that under specific circumstances, segmentectomy may provide comparable preservation of postoperative pulmonary function as traditional lobectomy. Further analysis showed significant increases in total NOL volume and ipsilateral NOL volume at various postoperative time points (1 month, 3 months, 6 months, and 1 year) in the lobectomy group, a trend not prominently seen in the segmentectomy group. This indicates that the non-affected lung portions may undergo more significant compensatory growth after lobectomy, possibly as a biological response to greater tissue removal. This aligns with findings by Ueda *et al.* (21), who suggested that lobectomy promotes postoperative expansion and compensation of the bilateral remaining lungs more substantially than segmentectomy. Similarly, Nomori *et al.* (22) argued that patients undergoing segmentectomy suffer less loss of functional lung tissue postoperatively, suggesting potential advantages of segmentectomy in preserving lung function. Notably, although the lobectomy group showed some degree of compensatory growth, our data also indicate that segmentectomy maintained relatively stable lung function postoperatively. This is reflected in the changes in contralateral LV ratio and WAL ratio at 1 year postoperatively, especially in the lobectomy group, where despite a significant increase in contralateral LV ratio, the WAL ratio decreased, suggesting that the quality of lung tissue may not solely correlate positively with its quantitative indices.

The observed compensatory changes provide insights into the adaptive capacity of postoperative residual lung tissue. A previous study by Hsia *et al.* (23) suggested that this compensatory expansion involves not only the overinflation of existing alveolar septa but also the increase in vital lung tissue, supported by microscopic and radiological assessments of lung morphology in adult dogs. Consistently, our study observed a higher proportion of patients in the lobectomy group showing an increase in NOL tissue volume, indicating a more significant compensatory response, likely driven by the removal of more functional lung tissue. Over time, the gradual increase in NOL volume observed in the lobectomy group may reflect the ongoing adaptation and redistribution of respiratory load. In contrast, the segmentectomy group exhibited minimal compensatory changes, suggesting a more limited response in lung tissue expansion, aligning with the view that segmentectomy, by preserving most lung tissue, minimally disrupts overall lung function and compensatory mechanisms. These observations support previous studies, revealing better preservation of lung function after segmentectomy compared to lobectomy (11,24,25). However, it is noteworthy that long-term follow-ups are necessary to evaluate the persistence of these compensatory changes and their impact on patient outcomes. Post-lung cancer surgery, compensatory growth of lung tissue is crucial for restoring normal lung function. Alveolar regeneration and vascular remodeling are key components of this process, involving the expansion of unharmed alveoli in the residual lung tissue, formation of new alveoli, and generation of new blood vessels along with adjustments to the existing vascular network to accommodate the altered lung tissue structure. Quantitative CT analysis, by providing precise measurements of LV and density, can objectively reflect these microchanges, offering an advantage over traditional PFTs by providing direct quantification of lung tissue structure and function status without relying on patient cooperation.

The association of higher preoperative WAL% of

Table 5 Sequential CT follow-up at 3 months, 6 months, and 1 year postoperatively

Characteristics	Lobectomy group					Segmentectomy group				
	Preoperative CT	3 months follow-up CT	6 months follow-up CT	1 year follow-up CT	P value	Preoperative CT	3 months follow-up CT	6 months follow-up CT	1 year follow-up CT	P value
Total lung										
MLD (HU)	−814.05 (−832.75, −773.3)	−817.95 (−837.45, −787.25)	−820.7 (−845.3, −799.5)	−829.95 (−848.05, −804.5)	<0.001	−824.15 (−835.75, −797.15)	−813.8 (−833.05, −791.9)	−812.4 (−838.85, −808.6)	−820.2 (−831.45, −817.45)	0.13
LV (cm^3)	4,221.1 (3,576.55, 4,827.95)	3,488.7 (2,626.05, 4,108.5)	3,627.25 (3,028.25, 4,181.6)	3,637.2 (3,245, 4,054.75)	<0.001	4,650.8 (3,962.3, 5,233.4)	4,247.15 (3,445.3, 4,649.05)	4,259.45 (3,605.15, 4,803.35)	4,096.35 (3,796.95, 4,765.65)	0.005
WAL (cm^3)	3,539.2 (2,780.1, 4,162.35)	2,552.03 (1,524.42, 3,109.4)	2,855.7 (1,880.82, 3,365.77)	3,015.25 (2,132.85, 3,235.7)	<0.001	3,975.7 (2,963.4, 4,470.85)	3,242.9 (2,679.35, 3,863.6)	3,490.4 (2,880.75, 4,015.25)	3,406.55 (3,214.45, 3,989.6)	0.02
WAL%	83.98 (75.85, 86.58)	76.72 (52.9, 83.05)	79.15 (61.2, 84.64)	80.97 (65.35, 85.87)	<0.001	84.5 (79.29, 86.21)	80.03 (76.04, 83.35)	81.88 (77.99, 84.63)	83.41 (79.1, 84.6)	0.21
EI	0.82 (0.25, 2.37)	0.96 (0.32, 2.55)	1.03 (0.41, 2.68)	0.96 (0.32, 2.55)	0.13	0.64 (0.37, 1.98)	0.60 (0.23, 1.77)	0.66 (0.35, 1.83)	0.65 (0.3, 1.65)	0.09
NOL (cm^3)										
MLD (HU)	−811.34 (−832.3, −749.26)	−819.43 (−822.6, −787.12)	−821.1 (−835.02, −791.45)	−826.62 (−847.8, −802.34)	0.03	−822.14 (−856.3, −796.42)	−828.5 (−847.23, −810.03)	−821.44 (−851.7, −803.32)	−831.2 (−862.7, −820.01)	0.26
LV (cm^3)	3,311.05 (2,742.75, 3,933.60)	3,488.7 (2,626.05, 4,108.5)	3,627.25 (3,028.25, 4,181.6)	3,637.2 (3,245, 4,054.75)	<0.001	3,761.35 (3,071.3, 4,048.20)	3,687.45 (2,995.95, 3,885.9)	3,839.1 (3,109.15, 4,016.2)	3,667.6 (3,125.85, 3,999.65)	0.44
WAL (cm^3)	2,805.1 (1,772.5, 3,375.67)	2,687.51 (1,686.2, 3,451.2)	2,921.6 (1,982.1, 3,582.05)	2,965.4 (2,001.57, 3,702.83)	0.02	3,012.3 (1,897.5, 3,217.1)	2,738.58 (1,921.7, 3,038.4)	2,900.4 (1,969.5, 3,171.45)	2,802.23 (2,234.68, 3,416.1)	0.06
WAL%	81.51 (73.2, 87.36)	79.7 (63.85, 85.2)	80.33 (71.12, 86.7)	81.69(70.02, 88.7)	0.15	82.3 (80.27, 85.9)	80.25(76.16, 83.9)	79.2 (72.52, 85.02)	81.2 (80.01, 85.34)	0.04
EI	0.8 (0.42, 1.97)	0.88 (0.32, 2.02)	0.93 (0.32, 2.54)	0.82 (0.28, 2.7)	0.11	0.68 (0.31, 1.27)	0.68 (0.25, 1.59)	0.69(0.4, 1.61)	0.62 (0.24, 1.88)	0.03
Ipsilateral NOL (cm^3)										
MLD (HU)	−800.2 (−825.3, −775.4)	−812.4 (−835.6, −791.5)	−820.9 (−845.0, −799.7)	−827.6 (−851.3, −805.8)	<0.001	−818.1 (−835.5, −789.4)	−825.5 (−847.0, −807.2)	−832.6 (−852.3, −815.3)	−839.2 (−861.1, −822.4)	0.13
LV (cm^3)	1,200.35 (1,012.90, 1,554.60)	1,342.5 (1,094.1, 1,647.5)	1,541.35 (1,295.9, 1,733.5)	1,587.85 (1,321.55, 1,787.75)	<0.001	1,380.80 (1,200.10, 1,502.50)	1,392.05 (1,086.1, 1,562.4)	1,317.3 (1,087.65, 1,544.05)	1,370.4 (1,161.05, 1,688.6)	0.16
WAL (cm^3)	1,074.7 (776.3, 1,374.1)	1,037.3 (866.5, 1,451.2)	1,173.2 (958.7, 1,578.5)	1,284.5 (1,034.2, 1,702.1)	<0.001	1,066.1 (898.575, 1,247.9)	1,087.75 (912.675, 1,338.225)	1,115.4 (935.2, 1,370.1)	1,142.8 (961.4, 1,416.5)	0.56
WAL%	83.27 (75.51, 86.72)	79.24 (62.65, 85.28)	81.57 (66.2, 86.1)	83.49 (69.1, 87.3)	0.01	84.42 (80.88, 88.00)	83.66 (79.06, 86.76)	85.12 (81.5, 88.0)	86.21 (82.9, 88.5)	0.24
EI	0.98 (0.55, 1.78)	0.90 (0.45, 2.18)	0.86 (0.51, 2.37)	0.83 (0.56, 2.55)	0.09	0.61 (0.37, 1.34)	0.60 (0.23, 1.77)	0.66 (0.35, 1.68)	0.71 (0.41, 2.01)	0.07

Data are presented as median (Q1, Q3). P values comparing with pre-operation and follow-up CT are from Mann-Whitney *U* test. CT, computed tomography; MLD, mean lung density; HU, Hounsfield unit; LV, lung volume; WAL, well-aerated lung; WAL%, percentage of the WAL to total (or unilateral) LV; EI, emphysema index; NOL, non-operated lung.

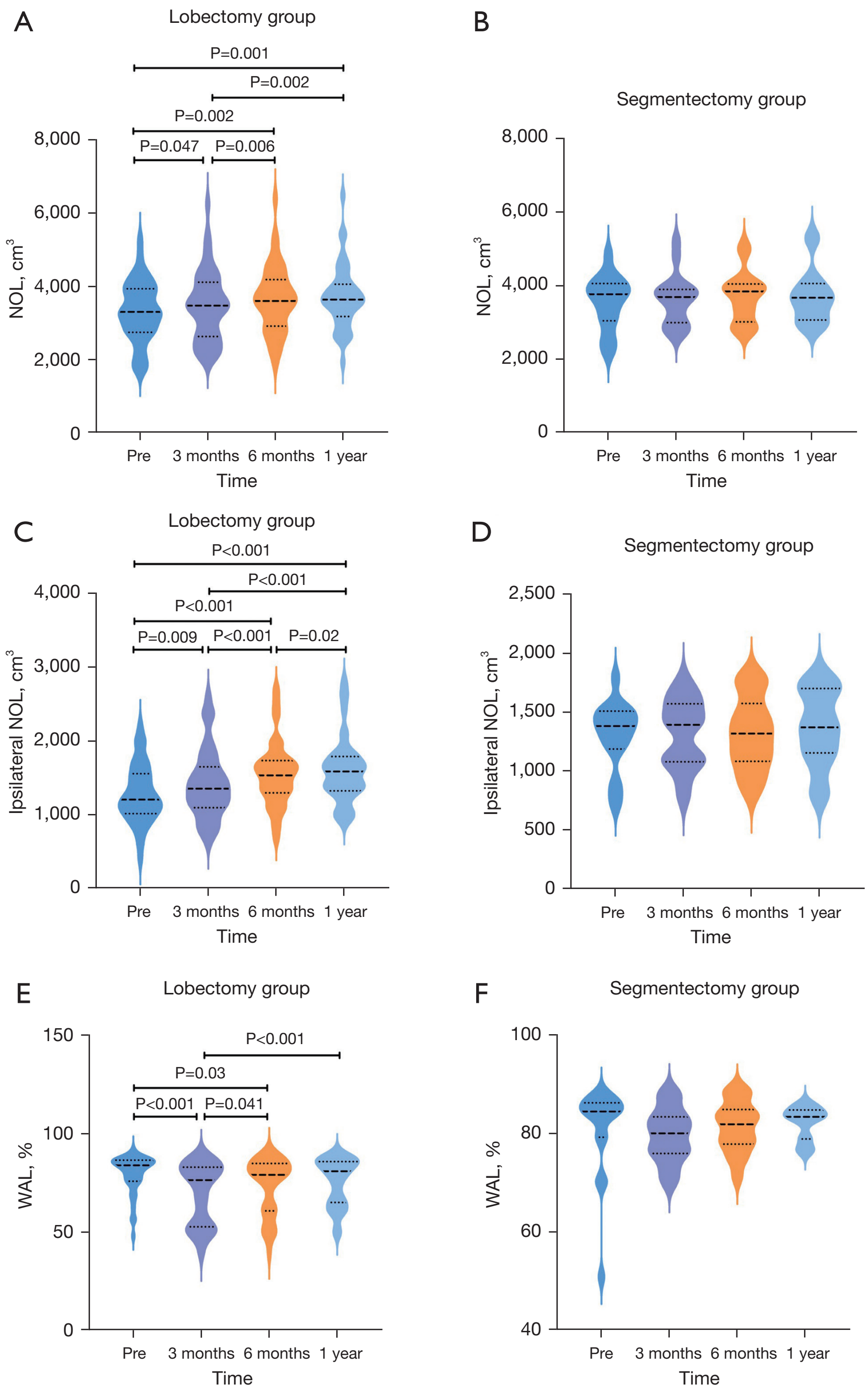

Figure 3 Analysis of quantitative parameter changes in preoperative CT and follow-up CT scans at 3 months, 6 months, and 1 year postoperatively. NOL, non-operated lung; pre, pre-operation; WAL%, percentage of the WAL to total (or unilateral) LV; WAL, well-aerated lung; LV, lung volume; CT, computed tomography.

ipsilateral NOL with a decline in WAL% 1 year post-surgery in the lobectomy group might reflect a complex biological phenomenon. A higher preoperative WAL% suggests better pulmonary gas exchange capacity and fewer lung parenchymal lesions. Theoretically, this should predict better postoperative lung function recovery. However, following lobectomy, as a larger portion of lung tissue is removed, the remaining lung tissue must take on more function, leading to a quicker depletion of functional capacity and potentially lower chances of compensatory growth, which may explain why a higher preoperative WAL% is associated with a decline in WAL% postoperatively. Additionally, this implies that the adaptive reorganization of lung tissue post-surgery may not solely depend on preoperative functional status but is also influenced by the efficiency of postoperative compensatory mechanisms. For the segmentectomy group, preoperative contralateral MLD was a predictor of WAL% decline postoperatively. MLD, an indicator of lung tissue density, reflects lung health status and severity of disease. Segmentectomy surgeries typically remove less tissue, and postoperative compensatory growth in lung tissue may depend more on the health status of the non-removed lung portions. A lower preoperative contralateral MLD reflects poorer lung tissue quality, possibly limiting postoperative compensatory growth capacity, hence a larger proportion of WAL% decline. This emphasizes the importance of a comprehensive assessment of overall lung function and lung tissue quality when considering lung surgery.

EI is an essential parameter for assessing the extent of emphysematous changes in the lung parenchyma (19,26). Yang *et al.*'s study shows that the incidence of lung cancer increases with the severity of emphysema, particularly with a significant correlation between centrilobular emphysema and lung cancer (27). In our study, the analysis of EI revealed notable differences in postoperative outcomes between the lobectomy and segmentectomy groups. Specifically, while both groups experienced changes in EI following surgery, the segmentectomy group showed a more pronounced decrease in the EI of the NOL over time. This decline in EI in the segmentectomy group suggests a potential reduction in emphysematous changes or improved aeration in the remaining lung parenchyma postoperatively. The preservation of lung parenchyma in segmentectomy, as opposed to lobectomy, likely contributes to this outcome. The segmentectomy group retained more functional lung tissue, which may have facilitated better overall pulmonary function and reduced stress on the NOL.

It must be acknowledged that this study has certain limitations. One limitation is the lack of tumor size matching between the two groups. This discrepancy stems from different surgical indications for segmentectomy and lobectomy, resulting in larger tumors in the lobectomy group compared to the segmentectomy group. It is proposed that patients with larger tumors are more likely to undergo lobectomy, potentially with reduced preoperative lung function compared to cases with smaller tumors. Moreover, the relatively small sample size and the limited number of cases with 2-year follow-up preclude analysis, necessitating future studies with longer duration and larger sample sizes to validate these findings and assess the duration of observed compensatory changes.

Conclusions

In conclusion, this study evaluates the impact of lobectomy and segmentectomy on postoperative pulmonary function and compensatory LV changes in lung cancer patients using quantitative CT technology. It reveals that both surgical methods lead to a decline in the WAL%. However, the lobectomy group exhibited a more pronounced compensatory increase in NOL volume, suggesting that more extensive tissue removal may enhance the adaptive capacity of the remaining lung tissue. Moreover, postoperative pulmonary function changes were closely related to preoperative lung density and WAL% of the NOL, underscoring the value of quantitative CT in predicting postoperative pulmonary function changes. These findings hold significant clinical implications for optimizing lung cancer surgical strategies, guiding personalized treatment choices, and balancing tumor control with postoperative pulmonary function preservation to improve patients' quality of life.

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Footnote

Reporting Checklist: The authors have completed the STROBE reporting checklist. Available at https://jtd.amegroups.com/article/view/10.21037/jtd-24-492/rc

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Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://jtd.amegroups.com/article/view/10.21037/jtd-24-492/coif). S.G. reports that he is an employee of Philips Healthcare. The other authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. This retrospective, single-center study was approved by the Ethics Committee of Wuhan Union Hospital, Wuhan, China (No. 0526), which waived the requirement for informed consent due to the retrospective nature of the study. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013).

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