Three–dimensional computed tomographic volumetry precisely predicts postoperative pulmonary function

（3D-CT による肺容量測定は，正確に術後肺機能を予測する）

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Abbreviations

3D-CT = three-dimensional computed tomographic

COPD = chronic obstructive pulmonary disease

SC = segment counting

VC = vital capacity

FEV1 = forced expiratory volume in 1 second

DLco = diffusion capacity of the lung for carbon monoxide

HU = Hounsfield units

LAA = low-attenuation area

FLV = functional lung volume

ppo- = predicted postoperative

post- = measured postoperative

SD = standard deviation

LOA = limits of agreement

Abstract

Purpose: It is important to accurately predict the patient's postoperative pulmonary function. The aim of this study was to compare the accuracy of predictions of the postoperative residual pulmonary function obtained with three-dimensional computed tomographic (3D-CT) volumetry with that of predictions obtained with the conventional segment-counting method.

Methods: Fifty-three patients scheduled to undergo lung cancer resection, pulmonary function tests, and computed tomography were enrolled in this study. The postoperative residual pulmonary function was predicted based on the segment-counting and 3D-CT volumetry methods. The predicted postoperative values were compared with the results of postoperative pulmonary function tests.

Results: Regarding the linear correlation coefficients between the predicted postoperative values and the measured values, those obtained using the 3D-CT volumetry method tended to be higher than those acquired using the segment-counting method. In addition, the variations between the predicted and measured values were smaller with the 3D-CT volumetry method than with the segment-counting method. These results were more obvious in COPD patients than in non-COPD patients.

Conclusions: My findings suggested that the 3D-CT volumetry was able to predict the residual pulmonary function more accurately than the segment-counting method, especially in patients with COPD. This method might lead to the selection of appropriate candidates for surgery among patients with a marginal pulmonary function.

Keywords: three-dimensional computed tomographic volumetry, segment-counting method, residual pulmonary function, chronic obstructive pulmonary disease

Introduction

Surgical resection remains the principal treatment for early stage lung cancer, although new chemotherapeutic agents and molecular-targeted drugs have been developed. However, surgical resection cannot be used to treat patients with a poor pulmonary function or complications such as chronic obstructive pulmonary disease (COPD) and interstitial pneumonitis [1,2]. In order to conduct pulmonary resection safely, it is necessary to ensure that the patient's postoperative pulmonary function remains above acceptable levels [3].

The prediction of the residual pulmonary function after lung resection has conventionally been performed using the segment-counting method [4,5]. However, the segment-counting method is based solely on the number of remaining pulmonary segments, and differences between the volumes of each segment are ignored. These issues are expected to interfere with the prediction of the postoperative residual pulmonary function. It was reported that three-dimensional computed tomographic (3D-CT) volumetry produces more accurate predictions of the postoperative residual pulmonary function than the segment-counting method [6-8], and its use for such purposes might help reduce the frequency of postoperative complications [9,10]. In particular, patients with a poor preoperative pulmonary function, such as those with COPD, suffer more postoperative problems than those with a normal pulmonary function [11,12].

The purpose of the present study was to compare the accuracy of the postoperative residual pulmonary function predicted using 3D-CT volumetry with that predicted using the conventional segment-counting method in lung cancer patients, especially those with a poor pulmonary function.

Methods

Patients

The subjects of this study were 53 patients who underwent anatomical lung resection for primary lung cancer from April 2012 to March 2014. All of the patients underwent a pulmonary function test and thin-slice computed tomography prior to surgery. Six months after surgery, they underwent a pulmonary function test again. The postoperative pulmonary functions predicted using the segment-counting and 3D-CT methods were compared among the same patients. Patient data, including the age, sex, smoking habits, tumor location, resection site, and pulmonary function test variables, were collected. The patients' clinical characteristics are shown in Table 1. COPD was defined according to the Global Initiative on Obstructive Lung Disease Guidelines. Patients with COPD, who were those with forced expiratory volume in 1 second percentage ($FEV_{1\%}$) values of <70%, accounted for 43.4% of the study population (23/53). All patients were informed about the research protocol and provided their written consent. This study was performed as a clinical trial and approved by the institutional review board of the Tsukuba University School of Medicine. The approval number was H24-66.

CT examinations

All preoperative CT examinations were performed using 64-row multi-slice helical CT (Brilliance 64; PHILIPS Electronics, Tokyo, Japan) and 256-row multi-slice helical CT (Brilliance iCT 256; PHILIPS Electronics) scanners. CT images 1-mm-thick covering the entire lung were obtained using the following parameters for the 64- and 256-row scanners with the patient in the supine position: deep inspiratory breath-holding; gantry rotation speed: 0.5 and 0.33

seconds, respectively; table speed: 41.2 and 183.8 mm/s, respectively; beam collimation: 64×0.625 and 128×0.625 mm, respectively; beam pitch: 0.515 and 0.758, respectively; peak tube voltage: 120 kv; tube current exposure time product: 180-280 mAs; and pixel resolution: 512 × 512. Contrast medium was intravenously administered to delineate the boundaries between the tumor and mediastinal structures. A single-phase scan was obtained after 30 seconds of peripheral intravenous power injection of 100 mL of non-ionic iodine contrast medium (Iomeron 300; Bracco, Milano, Italia) at a rate of 1.6 to 3.0 mL/sec, depending on the size of the patient.

Pulmonary function tests

Pulmonary function tests, which assessed the vital capacity (VC), forced expiratory volume in 1 second (FEV_1), $FEV_{1\%}$, and the diffusing capacity of the lung for carbon monoxide (DLco), were performed within one month prior to surgery and at six months after surgery with patients in the seated position.

3D-CT volumetry and emphysema analyses

All thin-slice CT data for each patient were transferred to a computer workstation (SYNAPSE VINCENT ver.3.0; FUJIFILM, Tokyo, Japan), on which 3D lung models were reconstructed. The 3D models could be viewed at multiple angles on the computer display, and the bronchial territory could be accurately extracted by designating the target segment or lobar bronchus. Furthermore, it was possible to calculate the volume of each extracted territory. The volumes of the trachea, bronchus, pulmonary artery, pulmonary vein, tumor, and other parenchymal structures, such as the tissues affected by atelectasis or organizing lesions, were calculated semi-automatically and selectively removed from the 3D lung models. To evaluate the extent of emphysematous lung lesions, the proportion of the lung occupied by low-attenuation areas (LAA) was calculated by highlighting the areas with attenuation values of less than –910 Hounsfield units (HU) [6,13-17]. The normal lung volume was calculated after excluding the emphysematous lung volume. In this study, LAA accounted for 13.44% of the lung tissue on average (Table 1). Finally, the volumes of the respiratory tract, blood vessels, tumor, and other parenchymal structures were excluded to determine the volume of the lung tissue that participates in breathing, which was called the functional lung volume (FLV) (Fig. 1) [6,13].

Proportional volume of each segment

Prior to the prediction of the residual pulmonary function, I examined whether or not there were marked variation in the proportional volume of each segment. All segmental bronchi were designated in all patients, and the volume of each segment was calculated using 3D-CT volumetry. The proportional volume of each segment relative to the volume of the whole lung was calculated. In the segment-counting method, because it is assumed that all segments except the left upper division are the same size, the proportional volume is calculated as follows: 1/19 ≒ 5.26%; and the proportional volume of the left upper division is calculated as follows: 1.5 / 19 ≒ 7.89%. In the 3D-CT volumetry method, the volume of each segment was calculated and compared with the volume of the same segment according to the segment-counting method.

Segment-counting and 3D-CT volumetry methods

The postoperative residual pulmonary function was predicted based on the segment-counting and 3D-CT volumetry methods using the formula and methods developed by Ali et al. and Gass GD et al., as described below [4,5].

$$\text{Predicted postoperative VC or FEV}_1 \text{ or DLco (ppo-VC, ppo-FEV}_1\text{, ppo-DLco)} =$$

$$(1 - A / 19) \times \text{preoperative VC or FEV}_1 \text{ or DLco}$$

In the segment-counting method, A represents the total number of unobstructed segments in the resection lobe, which was assumed to be 3, 2, and 5 for the right upper, middle, and lower lobe, respectively, and 3, 2, and 4 for the left upper segment, lingular segment, and lower lobe, respectively, and 19 is the total number of segments in the whole lung. In the 3D-CT volumetry method, A represents the FLV of the resection portion of the lung, and the total number of segments is replaced by the total volume of the FLV of the whole lung.

The predicted postoperative values were compared with the postoperative measurements obtained at six months after the operation (post-VC, post-FEV_1, post-DLco).

Statistical analyses

Data are reported as the mean ± standard deviation (SD) or median and range. The two-sample t-test, Kruskal-Wallis test, and Mann-Whitney U test were used to examine the relationships between categorical and numerical variables. The relationships between the measured and estimated numerical variables were determined using Pearson's correlation coefficient and a linear regression analysis. The difference in the correlation coefficients was also assessed. Agreement between the predicted and measured numerical variables was analyzed by the Bland-Altman method to evaluate the variation. The limits of agreement were defined as the range of two standard deviations from the mean difference between the predicted and measured numerical variables. P-values of <0.05 were considered significant. PASW Statistics 18 (SPSS, Chicago, IL, USA) was used for all analyses.

Results

The patients' clinical characteristics are shown in Table 1. The total number of patients in this study was 53. There were 30 non-COPD patients (56.6%) and 23 COPD patients (43.4%). Compared with the non-COPD patients, the COPD patients were significantly older, included more smokers, and had lower FEV1, FEV1%, and DLco values. In addition, the postoperative FEV_1, $FEV_{1\%}$, and DLco values of the COPD patients were significantly lower than those of the non-COPD patients.

The proportional volume measurements obtained for each segment with the 3D-CT volumetry method differed significantly from those acquired with the segment-counting method, except in left segment 1+2 and segment 3 ($p < 0.01$) (Fig. 2). The proportional volume measurements for right segments 1, 3, and 6 and left segment 1+2 and segment 3 were significantly larger than the values predicted using the segment-counting method. In contrast, the proportional volume measurements for right segments 7 and 9 and left segments 4, 5, 6, and 9 were significantly smaller than those predicted using the segment-counting method. The proportional volume measurements obtained for each lobe with the 3D-CT volumetry method were compared with those acquired with the segment-counting method in the same manner. The proportional volume measurement for the right upper lobe was significantly larger than that predicted using the segment-counting method. In addition, the proportional volume measurements for the right lower lobe, left upper lobe, and left lower lobe were significantly smaller than those predicted using the segment-counting method (Table 2).

In the segment-counting method, the linear correlation coefficients for the relationships between ppo-VC and post-VC, ppo-FEV_1 and post-FEV_1, and ppo-DLco and post-DLco were 0.873 ($p < 0.01$), 0.845 ($p < 0.01$), and 0.826 ($p < 0.01$), respectively. In the 3D-CT volumetry method, the linear correlation coefficients for the relationships between ppo-VC and post-VC, ppo-FEV_1 and post-FEV_1, and ppo-DLco and post-DLco were 0.885 ($p < 0.01$), 0.884 ($p < 0.01$), and 0.843 ($p < 0.01$), respectively (Table 3). There were no significant differences between the linear correlation coefficients of the two prediction methods, but all of the linear correlation coefficients obtained with the 3D-CT volumetry method tended to be higher than those acquired with the segment-counting method.

In the segment-counting method, the limits of agreement between the predicted and postoperative measured values ranged from -0.66 to 0.66 in VC, from -0.63 to 0.37 in FEV_1, and from -6.31 to 4.09 in DLco. In the 3D-CT volumetry method, the limits of agreement between the predicted and postoperative measured values ranged from -0.60 to 0.64 in VC, from -0.55 to 0.33 in FEV_1, and from -5.94 to 3.98 in DLco. The ranges of the limits of agreement obtained with the 3D-CT volumetry method were smaller than those acquired with the segment-counting method (Table 4).

The differences between the predictions obtained with the 3D-CT volumetry and segment-counting methods were analyzed separately in the COPD and non-COPD groups. In the non-COPD group, the linear correlation coefficients for the relationships between ppo-VC and post-VC, ppo-FEV_1 and post-FEV_1, and ppo-DLco and post-DLco were 0.927, 0.877, and 0.905, respectively, when the segment-counting method was used ($p < 0.01$), whereas they were 0.929, 0.916, and 0.912, respectively, when the 3D-CT volumetry method was used ($p < 0.01$). In contrast, in the COPD group the linear correlation coefficients for the relationships between ppo-VC and post-VC, ppo-FEV_1 and post-FEV_1, and ppo-DLco and post-DLco were 0.740, 0.720, and 0.571, respectively, when the segment-counting method was used ($p < 0.01$), whereas they were 0.785, 0.775, and 0.603, respectively, when the 3D-CT volumetry method was used ($p < 0.01$) (Table 5). Although not to a significant degree, the differences between the linear correlation coefficients obtained with the two prediction methods tended to be larger in the COPD group than in the non-COPD group.

In the non-COPD group, the limits of agreement between the predicted and postoperative measured values ranged from -0.57 to 0.55 in VC, from -0.58 to 0.38 in FEV_1, and from -5.90 to 2.50 in DLco when the segment-counting method was used, whereas they ranged from -0.57 to 0.55 in VC, from -0.48 to 0.32 in FEV_1, and from -5.56 to 2.48 in DLco when the 3D-CT volumetry method was used. In contrast, in the COPD group, the limits of agreement between the predicted and postoperative measured values ranged from -0.74 to 0.78 in VC, from -0.70 to 0.34 in FEV_1, and from -6.35 to 5.69 in DLco when the segment-counting method was used, whereas they were from -0.64 to 0.76 in VC, from -0.63 to 0.33 in FEV_1, and from -5.99 to 5.49 in DLco when the 3D-CT volumetry method was used. The ranges of limits of agreement obtained with the 3D-CT volumetry method were smaller than those acquired with the segment-counting method in both the COPD group and non-COPD group. The differences between ranges of limits of agreement obtained with the two prediction methods were larger in the COPD group than in the non-COPD group, except for those of FEV_1 (Table 6).

The linear correlation coefficients were examined to identify the relationship between the preoperative $FEV_{1\%}$ and the proportion of LAA. In the COPD and non-COPD groups, the linear correlation coefficients for the relationship between the preoperative $FEV_{1\%}$ and the proportion of LAA was 0.605 ($p < 0.01$) and 0.112, respectively ($p=0.557$). A negative correlation between these variables was observed only in the COPD group.

Discussion

In recent years, the number of lung cancer patients with poor risk factors for surgery, such as elderly age or coexisting diseases like COPD or restrictive pulmonary disease, has been increasing. Therefore, it is important to accurately predict patients' postoperative residual pulmonary function in order to avoid postoperative respiratory function disorders. Originally, residual pulmonary function after lung resection had been predicted in the pneumonectomy. For this purpose, the bronchospirometric method, which tested pulmonary function by inserting an intrabronchial intubation tube into one side of the lungs, and the unilateral pulmonary artery occlusion test, which examined pulmonary and circulation change by occluding pulmonary artery, were used [18,19]. However, these methods are highly invasive and not able to cope with an operation less than lobectomy. Afterward, pulmonary ventilation and perfusion scintigraphy using radioisotopes were developed to check local pulmonary function less invasively [20,21]. These methods demonstrated relatively good correlation with the postoperative pulmonary function, but the radiation exposure to patients and technicians, and ventilation-perfusion imbalance due to gravity became problematic. Therefore, the segment-counting method, which predicts pulmonary function by calculating the number of segments to be resected, was devised. This simple method can predict the postoperative pulmonary function in a short time without performing any invasive examinations [4]. However, it was based solely on the number of remaining pulmonary segments, and did not take into account the heterogeneity of volume and function of every segment; therefore, it was unconvincing in terms of accuracy. To predict the postoperative pulmonary function more accurately, Wu et al. reported a quantitative CT method that predicts the postoperative pulmonary function by measuring the pulmonary volume on CT images [6]. The primitive quantitative CT method was a slice-by-slice method in which an observer manually delineates the outer perimeter of the lung on a large number of thin-section CT images. Although this manual method was accurate, it was extremely time-consuming and impractical for routine clinical use. As there is not a large difference between the quantitative CT and segment-counting methods for lobectomy, the segment-counting method has been used for postoperative pulmonary function prediction [22]. From the above mentioned process, 3D-CT volumetry using image software was developed to predict the postoperative pulmonary function more simply and accurately. In the present study, I demonstrated that the relative volume of each segment differed significantly, as shown in Fig. 2. Therefore, predictions obtained using the segment-counting method may differ from the actual postoperative values. Furthermore, the relative volumes of each segment differed between the 3D-CT volumetry and segment-counting methods. Iwano et al. reported that 3D-CT volumetry using the Synapse Vincent volume analyzer was able to measure lobar volumes more precisely than the segment-counting-method [23]. Therefore, the volume of the lung to be resected can be predicted more precisely with 3D-CT volumetry than with the segment-counting method. In the present study, it was demonstrated that the relative volume of each segment differed significantly, as shown in Fig. 2. Therefore, predictions obtained using the segment-counting method might differ from the actual postoperative values. Furthermore, the relative volumes of each segment differed between the 3D-CT volumetry and segment-counting methods. Iwano et al. reported that 3D-CT volumetry using the Synapse Vincent volume analyzer was able to measure lobar volumes more precisely than the segment-counting-method [23]. Therefore, the volume of the resection lung could be predicted more precisely with 3D-CT volumetry than with the segment-counting method.

The function of each pulmonary segment can vary between individuals and can also be affected by diseases, such as emphysema and fibrosis. The image analysis software program used in this study is able to calculate and exclude the volume of blood vessels and tumors as well as atelectasis or organizing lesions. Furthermore, it can exclude emphysematous lesions by excluding low-attenuation areas. The postoperative residual pulmonary function is therefore believed to be predicted more accurately using the FLV, which excludes such non-functioning lung volumes, than using the segment-counting method [6,14,15,24]. Since the volume and function of each segment differ by individual, the values predicted with the 3D-CT volumetry method are expected to be well correlated with the postoperative pulmonary function.

Although there is some software for pulmonary volumetry analysis, SYNAPSE VINCENT was used in this study for the following two points: First, the separation of pulmonary artery and vein, and each organ was possible by performing CT only in the venous phase, not in 2 arteriovenous phases. This was able to control organ shift due to breathing and reduce exposure to the patients [25]. In addition, accurate visualization of the pulmonary vein is important to revise errors in separation of pulmonary segments, which was an advantage over other software [26]. Second, automatic separation of the pulmonary lobe was possible with analysis of LAA and the %LAA of each pulmonary lobe was easily calculated in a short time [27]. Other software was only able to calculate the %LAA of total lung tissue or right and left lung separately, but not %LAA of each pulmonary lobe. This was useful to evaluate the function of each pulmonary lobe.

In the present study, the values predicted with the 3D-CT volumetry method tended to be more closely correlated with the actual postoperative measurements than the predicted values obtained with the segment-counting method. In addition, according to the differences between the ranges of limits of agreement by method, the variations between the predicted and actual measured values were smaller with the 3D-CT volumetry method than with segment-counting method. However, the difference between the correlation coefficients obtained with the two prediction methods was not very large among non-COPD patients, with the difference between the correlation coefficients obtained with the two prediction methods tending to be larger in the COPD group than in the non-COPD group. Furthermore, the ranges of the limits of agreement obtained with the 3D-CT volumetry method were smaller than those acquired with the segment-counting method in both the COPD and non-COPD groups.

The differences in the variations of values obtained with the two prediction methods were smaller in the COPD group than in the non-COPD group, except for $FEV_{1\%}$. This suggests that the 3D-CT volumetry method is able to predict the postoperative residual pulmonary function more accurately in COPD patients than in non-COPD patients. The proportion of the lungs occupied by LAA was 16.59 ± 14.83 and 11.02 ± 7.74 in the COPD and non-COPD groups, respectively, a non-significant difference. However, a negative correlation between the preoperative $FEV_{1\%}$ and the proportion of the lungs occupied by LAA was detected among the COPD patients but not the non-COPD patients. The 3D-CT volumetry method may be able to detect non-functioning lung tissue (i.e. LAA), which can negatively influence the $FEV_{1\%}$, enabling this method to precisely evaluate the FLV by excluding such non-functioning lung tissue, especially in cases of COPD. Accordingly, the precise evaluation of the FLV with the 3D-CT method seems to result in more accurate predictions of the postoperative pulmonary function than the segment-counting method, especially in COPD patients.

The main limitation of my study was that I did not consider the effects of lung volume reduction surgery. Lung volume reduction surgery removes emphysematous lesions and improves the lung function, possibly by increasing the airway conductance and the ratio of conductance to lung volume [28,29]. Therefore, in patients with severe COPD, both a reduction in the amount of functioning lung tissue and an improvement in the function of the residual lung have to be considered, and these factors will be taken into account in my future studies.

In conclusion, the segment volume can vary between segments and individuals; therefore, predictions of the residual pulmonary function obtained with the segment-counting method may be inaccurate. My findings suggest that the 3D-CT-volumetry method is able to predict the residual pulmonary function more accurately than the segment-counting method, as the actual volume loss can be calculated, which may facilitate the selection of appropriate candidates for lung cancer surgery and reduce the risk of surgical complications, especially in patients with a relatively poor pulmonary function, such as those with COPD.

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Table 1. Patients' clinical characteristics

Variables	Total (n=53)	Non-COPD ($FEV_{1\%}$ ≥70%) (n=30)	COPD (FEV1.0% <70%) (n=23)	P-value Non COPD vs. COPD
Age (years)	66 ± 11 (38-86)	63 ± 12 (38-79)	71 ± 8 (54-86)	0.01
Sex (male/female)	31/22	15/15	16/7	0.096
Pack-years smoked	36 ± 35 (0-116)	24 ± 32 (0-116)	51 ± 32 (0-108)	0.004
VC (l)	3.34 ± 0.78 (1.99-5.70)	3.31 ± 0.88 (1.99-5.70)	3.37 ± 0.65 (2.01-4.33)	0.781
FEV_1 (l)	2.30 ± 0.56 (1.15-4.10)	2.48 ± 0.58 (1.46-4.10)	2.07 ± 0.46 (1.15-2.86)	0.008
$FEV_{1\%}$ (%)	70.93 ± 9.34(46.60-91.10)	77.18 ± 5.61(70.00-91.11)	62.78 ± 6.47(46.60-69.80)	<0.001
DLco (ml/min/mmHg)	15.51 ± 4.94 (7.36-28.94)	16.75 ± 5.32 (7.36-28.94)	13.80 ± 3.67 (8.22-21.01)	0.03
Proportion of LAA (%)	13.44 ± 11.58 (0-56.90)	11.02 ± 7.74 (0-26.40)	16.59 ± 14.83 (0-56.90)	0.112
Resection site				0.224
Right upper lobe	13	7	6	
Right middle lobe	2	1	1	
Right lower lobe	11	6	5	
Left upper lobe	12	7	5	
Left lower lobe	10	6	4	
Others	5	3	2	
Postoperative VC (l)	2.62 ± 0.66 (1.55-4.41)	2.63 ± 0.73 (1.55-4.41)	2.61 ± 0.56 (1.74-4.10)	0.929
Postoperative FEV_1 (l)	1.93 ± 0.44 (1.12-3.06)	2.03 ± 0.47 (1.34-3.06)	1.79 ± 0.37 (1.12-2.38)	0.043
Postoperative $FEV_{1\%}$ (%)	74.89 ± 10.16 (52.30-93.50)	79.35 ± 7.77 (67.40-93.50)	69.07± 10.10 (52.30-89.90)	<0.001
Postoperative DLco (ml/min/mmHg)	13.27 ± 4.61 (4.95-25.00)	14.80 ± 4.89 (4.95-25.00)	11.29 ± 3.39 (5.07-22.18)	0.005

Data are expressed as the mean ± standard deviation (range). VC: vital capacity, FEV_1: forced expiratory volume in 1 second, $FEV_{1\%}$: forced expiratory volume in 1 second percentage. DLco: diffusing capacity of the lung for carbon monoxide, COPD: chronic obstructive pulmonary disease, LAA: low-attenuation areas

Table 2. Proportional volumes of various segments and lobes according to the 3D-CT and segment-counting methods

Segment/lobe	Proportional volume according to the 3D-CT method (%)	Proportional volume according to the SC method (%)	P-value
Rt. segment 1	6.70 (1.50 - 13.40)	5.26	0.007
Rt. segment 2	5.60 (2.10 - 12.00)	5.26	0.107
Rt. segment 3	9.10 (5.20 - 13.40)	5.26	<0.001
Rt. segment 4	5.00 (0.90 - 7.20)	5.26	0.107
Rt. segment 5	5.30 (1.60 - 10.40)	5.26	0.858
Rt. segment 6	5.70 (2.50 - 10.20)	5.26	0.049
Rt. segment 7	2.30 (0.60 - 5.50)	5.26	<0.001
Rt. segment 8	5.20 (1.40 - 9.20)	5.26	0.858
Rt. segment 9	3.70 (0.90 - 8.00)	5.26	<0.001
Rt. segment 10	4.90 (2.00 - 10.50)	5.26	0.21
Lt. segment 1+2	9.10 (4.70 - 18.00)	7.89	<0.001
Lt. segment 3	8.40 (4.90 - 17.60)	7.89	0.049
Lt. segment 4	4.00 (1.40 - 7.70)	5.26	<0.001
Lt. segment 5	3.00 (1.00 - 8.80)	5.26	<0.001
Lt. segment 6	4.50 (2.00 - 8.40)	5.26	<0.001
Lt. segment 8	5.40 (2.40 - 8.90)	5.26	0.107
Lt. segment 9	4.00 (1.70 - 7.70)	5.26	<0.001
Lt. segment 10	5.20 (2.40 - 10.00)	5.26	0.858
Right upper lobe	21.90 (10.60 - 36.50)	15.79	<0.001
Right middle lobe	10.30 (3.90 - 16.10)	10.53	0.21
Right lower lobe	22.90 (9.20 - 32.60)	26.32	<0.001
Left upper lobe	26.00 (17.50 - 39.10)	26.32	0.02
Left lower lobe	19.70 (12.30 - 14.60)	21.05	0.01

Data are expressed as the median (range). 3D-CT: three-dimensional computed tomography.

Table 3. The linear correlations between the predicted postoperative pulmonary function and the measured postoperative pulmonary function

Variables	Coefficient	P-value
ppo-VC, $_{SC}$ vs. post-VC	0.873	<0.01
ppo-VC, $_{CT}$ vs. post-VC	0.885	<0.01
ppo-FEV_1, $_{SC}$ vs. post-FEV_1	0.845	<0.01
ppo-FEV_1, $_{CT}$ vs. post-FEV_1	0.884	<0.01
ppo-DLco, $_{SC}$ vs. post-DLco	0.826	<0.01
ppo-DLco, $_{CT}$ vs. post-DLco	0.843	<0.01

ppo-VC: predicted postoperative vital capacity, ppo-VC, $_{SC}$: ppo-VC predicted using the segment-counting method, ppo-VC, $_{CT}$: ppo-VC predicted using 3D-CT volumetry, post-VC: measured postoperative VC, ppo-FEV_1: predicted postoperative forced expiratory volume in 1 second, ppo-FEV_1, $_{SC}$: ppo-FEV_1 predicted using the segment-counting method, ppo-FEV_1, $_{CT}$: ppo-FEV_1 predicted using 3D-CT volumetry, post-FEV_1: measured postoperative FEV_1, ppo-DLco: predicted postoperative diffusing capacity of the lung for carbon monoxide, ppo-DLco, $_{SC}$: ppo-DLco predicted using the segment-counting method, ppo-DLco, $_{CT}$: ppo-DLco predicted using 3D-CT volumetry, post-DLco: measured postoperative DLco

Table 4. An analysis of the limits of agreement between the predicted postoperative pulmonary function and the measured postoperative pulmonary function

Variables	Difference	LOA
ppo-VC, $_{SC}$ vs post-VC	0.00 ± 0.33	-0.66 to 0.66
ppo-VC, $_{CT}$ vs post-VC	0.02 ± 0.31	-0.60 to 0.64
ppo-FEV_1, $_{SC}$ vs post-FEV_1	-0.13 ± 0.25	-0.63 to 0.37
ppo-FEV_1, $_{CT}$ vs post-FEV_1	-0.11 ± 0.22	-0.55 to 0.33
ppo-DLco, $_{SC}$ vs post-Dlco	-1.11 ± 2.60	-6.31 to 4.09
ppo-DLco, $_{CT}$ vs post-Dlco	-0.98 ± 2.48	-5.94 to 3.98

The difference between the predicted and measured values is expressed as the mean ± standard deviation.

The limits of agreement (LOA) is expressed as a range of standard deviations from the mean difference.

ppo-VC: predicted postoperative vital capacity, ppo-VC, $_{SC}$: ppo-VC predicted using the segment-counting method, ppo-VC, $_{CT}$: ppo-VC predicted using 3D-CT volumetry, post-VC: measured postoperative VC, ppo-FEV_1: predicted postoperative forced expiratory volume in 1 second, ppo-FEV_1, $_{SC}$: ppo-FEV_1 predicted using the segment-counting method, ppo-FEV_1, $_{CT}$: ppo-FEV_1 predicted using 3D-CT volumetry, post-FEV_1: measured postoperative FEV_1, ppo-DLco: predicted postoperative diffusing capacity of the lung for carbon monoxide, ppo-DLco, $_{SC}$: ppo-DLco predicted using the segment-counting method, ppo-DLco, $_{CT}$: ppo-DLco predicted using 3D-CT volumetry, post-DLco: measured postoperative DLco

Table 5. The linear correlations between the predicted postoperative pulmonary function and the measured postoperative pulmonary function in the COPD and non-COPD groups

	Non-COPD group (n=30)		COPD group (n=23)	
Variables	Coefficient	P-value	Coefficient	P-value
ppo-VC, $_{SC}$ vs. post-VC	0.927	<0.01	0.740	<0.01
ppo-VC, $_{CT}$ vs. post-VC	0.929	<0.01	0.785	<0.01
ppo-FEV_1, $_{SC}$ vs. post-FEV_1	0.877	<0.01	0.720	<0.01
ppo-FEV_1, $_{CT}$ vs. post-FEV_1	0.916	<0.01	0.775	<0.01
ppo-DLco, $_{SC}$ vs. post-DLco	0.905	<0.01	0.571	<0.01
ppo-DLco, $_{CT}$ vs. post-DLco	0.912	<0.01	0.603	<0.01

ppo-VC: predicted postoperative vital capacity, ppo-VC, $_{SC}$: ppo-VC predicted using the segment-counting method, ppo-VC, $_{CT}$: ppo-VC predicted using 3D-CT volumetry, post-VC: measured postoperative VC, ppo-FEV_1: predicted postoperative forced expiratory volume in 1 second, ppo-FEV_1, $_{SC}$: ppo-FEV_1 predicted using the segment-counting method, ppo-FEV_1, $_{CT}$: ppo-FEV_1 predicted using 3D-CT volumetry, post-FEV_1: measured postoperative FEV_1, ppo-DLco: predicted postoperative diffusing capacity of the lung for carbon monoxide, ppo-DLco, $_{SC}$: ppo-DLco predicted using the segment-counting method, ppo-DLco, $_{CT}$: ppo-DLco predicted using 3D-CT volumetry, post-DLco: measured postoperative DLco

Table 6. An analysis of the limits of agreement between the predicted postoperative pulmonary function and the measured postoperative pulmonary function in the COPD and non-COPD groups

	Non-COPD group (n=30)		COPD group (n=23)	
Variables	difference	LOA	difference	LOA
ppo-VC, $_{SC}$ vs post-VC	-0.01 ± 0.28	-0.57 to 0.55	0.02 ± 0.38	-0.74 to 0.78
ppo-VC, $_{CT}$ vs post-VC	-0.01 ± 0.28	-0.57 to 0.55	-0.06 ± 0.35	-0.64 to 0.76
ppo-FEV_1, $_{SC}$ vs post-FEV_1	-0.10 ± 0.24	-0.58 to 0.38	-0.18 ± 0.26	-0.70 to 0.34
ppo-FEV_1, $_{CT}$ vs post-FEV_1	-0.08 ± 0.20	-0.48 to 0.32	-0.15 ± 0.24	-0.63 to 0.33
ppo-DLco, $_{SC}$ vs post-Dlco	-1.70 ± 2.10	-5.90 to 2.50	-0.33 ± 3.01	-6.35 to 5.69
ppo-DLco, $_{CT}$ vs post-Dlco	-1.54 ± 2.01	-5.56 to 2.48	-0.25 ± 2.87	-5.99 to 5.49

The difference between the predicted and measured values is expressed as the mean ± standard deviation.

The limits of agreement (LOA) is expressed as a range of standard deviations from the mean difference.

ppo-VC: predicted postoperative vital capacity, ppo-VC, $_{SC}$: ppo-VC predicted using the segment-counting method, ppo-VC, $_{CT}$: ppo-VC predicted using 3D-CT volumetry, post-VC: measured postoperative VC, ppo-FEV_1: predicted postoperative forced expiratory volume in 1 second, ppo-FEV_1, $_{SC}$: ppo-FEV_1 predicted using the segment-counting method, ppo-FEV_1, $_{CT}$: ppo-FEV_1 predicted using 3D-CT volumetry, post-FEV_1: measured postoperative FEV_1, ppo-DLco: predicted postoperative diffusing capacity of the lung for carbon monoxide, ppo-DLco, $_{SC}$: ppo-DLco predicted using the segment-counting method, ppo-DLco, $_{CT}$: ppo-DLco predicted using 3D-CT volumetry, post-DLco: measured postoperative DLco

Fig. 1. The bronchial territories were extracted from three-dimensional lung models by specifying the target segment or lobe, and the volume of each territory was calculated concurrently. The volumes of the respiratory tract, blood vessels, tumors, and other parenchymal structures, such as tissue affected by atelectasis or organizing lesions, were calculated semi-automatically or selectively. The proportion of the lungs occupied by low-attenuation areas was calculated by highlighting the areas with attenuation values of less than –910 HU. The total lung volume, except for the volume of the lung tissue that does not participate in breathing, was described as the functional lung volume.

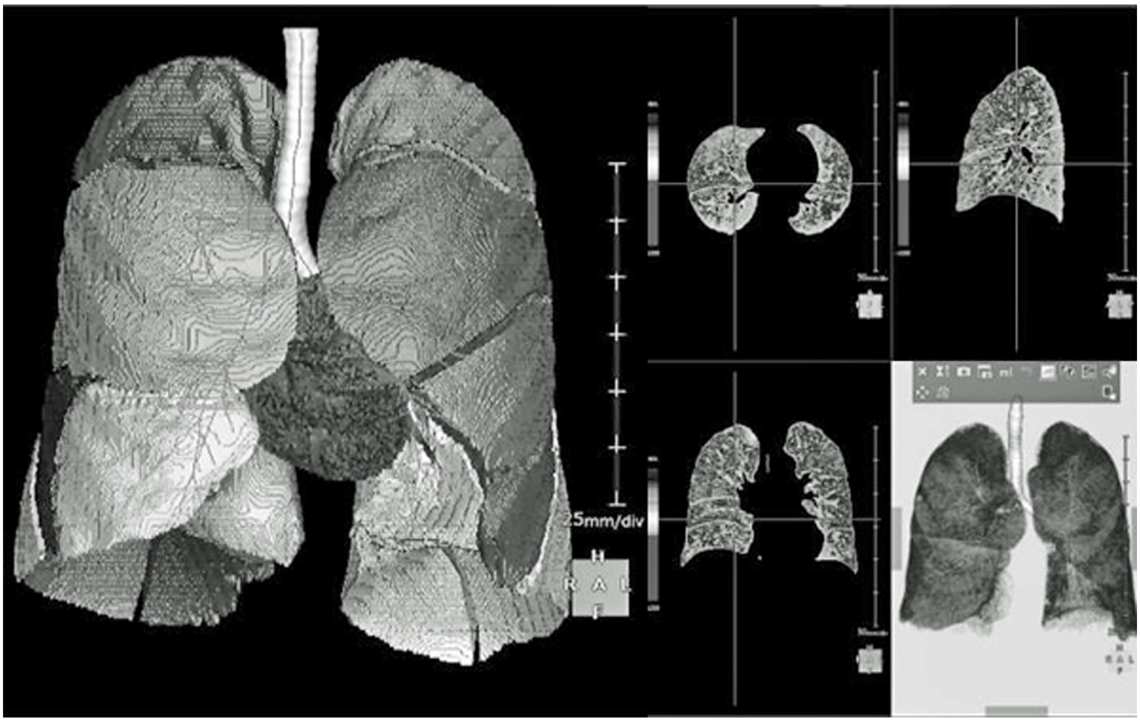

Fig. 2. The proportional volume of each segment is shown as a box and whisker plot. The central line indicates 1/19 ×100 = 5.26%, which is the volume ratio of 1 segment according to the segment-counting method. Significant differences were determined using the Kruskal–Wallis test (p <0.01). RU = right upper lobe, RM = right middle lobe, RL = right lower lobe, LU = left upper lobe, LL = left lower lobe.