Comparison of Lung, Lobe, and Airway Volumes between Supine and Upright Computed Tomography and Their Correlation with Pulmonary Function Test in Patients with Chronic Obstructive Pulmonary Disease

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Keywords
Chronic obstructive pulmonary disease · Lung volume measurements · Multidetector computed tomography · Posture · Standing position

Abstract
Background: Correlations between upright CT and pulmonary function test (PFT) measurements, and differences in lung/lobe/airway volumes between supine and standing positions in patients with chronic obstructive pulmonary disease (COPD) remain unknown. Objectives: The study aimed to evaluate correlations between lung/airway volumes on both supine and upright CT and PFT measurements in patients with COPD, and compare CT-based inspiratory/expiratory lung/lobe/airway volumes between the two positions. Methods: Forty-eight patients with COPD underwent both conventional supine and upright CT in a randomized order during inspiration and expiration breath-holds, and PFTs within 2 h. We measured the lung/lobe/airway volumes on both CT. Results: The correlation coefficients between total lung volumes on inspiratory CT in supine/standing position and PFT total lung capacity and vital capacity were 0.887/0.920 and 0.711/0.781, respectively; between total lung volumes on expiratory CT in supine/standing position and PFT functional residual capacity and residual volume, 0.676/0.744 and 0.713/0.739, respectively; and between airway volume on inspiratory CT in supine/standing position and PFT forced expiratory volume in 1 s, 0.471/0.524, respectively. Inspiratory/expiratory bilateral upper and right lower lobe, bilateral lung, and airway volumes were significantly higher in the standing than supine position (3.6–21.2% increases, all \( p < 0.05 \)); however, inspiratory/expiratory right middle lobe volumes were significantly lower in the standing position (4.6%/15.9% decreases, respectively, both \( p < 0.001 \)). Conclusions: Upright CT-based volumes were more correlated with PFT measurements than supine CT-based volumes in patients with COPD. Unlike other lobes and airway, inspiratory/expiratory right middle lobe volumes were significantly lower in the standing than supine position.

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Introduction

Chronic obstructive pulmonary disease (COPD) is a generally treatable and preventable disease characterized by persistent respiratory symptoms and limited air flow [1], representing the third leading cause of death worldwide [2]. The pulmonary function test (PFT) is the gold standard for diagnosing and staging the severity of COPD; however, the role of computed tomography (CT) has been expanded both in clinical practice and in research [3]. As of June 2022, there have been more than 500 million confirmed coronavirus disease 2019 cases and at least 6 million deaths worldwide [4]. Although PFTs are essential for COPD diagnosis and management, many PFT laboratories significantly reduced their testing capacity to reduce the spread of coronavirus disease 2019 [5]. Therefore, from a clinical perspective, an alternative to conventional PFTs would be desirable in situations where PFTs cannot be performed, such as an infectious disease pandemic [5].

An upright 320-detector-row CT scanner has recently been developed to assess the three-dimensional anatomy of the human body in the upright position [6]. This scanner enables the acquisition of isotropic volumetric data (0.5-mm voxel size) for the whole chest in approximately 5 s [7, 8]. A previous study reported that upright CT could predict PFT measurements, such as total lung capacity, functional residual capacity, and inspiratory capacity, more reliably than conventional supine CT in a volunteer cohort without any symptoms [8]. Although several previous studies have evaluated the correlation of lung volumes between conventional supine CT and PFT [9–11], to the best of our knowledge, no clinical study has evaluated the correlation between upright CT volumes and PFT measurements in patients with COPD. Furthermore, to our knowledge, no study has accurately evaluated the volume of each lung lobe in the standing position in patients with COPD [12]. PFTs are performed in the upright position; thus, we hypothesized that compared with supine CT, upright CT-based volumes would be more correlated with PFT measurements in patients with COPD, and upright CT could be a potential alternative to PFTs. We also hypothesized that each lobe volume in patients with COPD would be different between the supine and standing positions because the gravity direction in relation to the chest differs between the positions.

This study aimed to evaluate the correlations between lung/airway volumes on both supine and upright CT and PFT measurements in patients with COPD. Moreover, we aimed to compare CT-based inspiratory/expiratory lung, lobe, and airway volumes between the supine and standing positions.

Materials and Methods

Study Population

This prospective crossover study was approved by the Keio University School of Medicine Ethics Committee (No. 20160385) and was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all patients (UMIN Clinical Trials Registry (UMIN-CTR): UMIN000026587). From August 2018 to September 2019, 51 consecutive patients with known COPD, who were scheduled for clinical CT examination, were considered for inclusion in this study. The exclusion criteria were as follows: age <20 years (n = 0); pregnancy or unknown pregnancy status in patients with childbearing potential (n = 0); inability to undergo CT in a standing position (n = 0); or unwillingness to provide written informed consent (n = 0); or FEV1/FVC >70% on the same day of upright and supine CT examinations (n = 3). The remaining 48 patients were included in this study (Fig. 1). The data of the 48 enrolled patients were analyzed in a previous study that evaluated the airway luminal areas [12] but not lung, lobe, and airway volumes. COPD was classified into spirometric grades 1–4 in accordance with the global initiative for chronic obstructive lung disease (GOLD) recommendations using the corresponding percent predicted FEV1 [1].

CT Imaging Protocol

All patients underwent both chest low-radiation-dose CT in the supine position with their arms raised (Fig. 2a) and upright
chest low-radiation-dose CT in the standing position with their arms lowered (Fig. 2b) in a randomized order within 1 h on the same day. The conventional and upright CT scans were performed using a conventional 320-detector-row CT (Aquilion ONE; Canon Medical Systems, Otawara, Japan) and upright 320-detector-row CT (prototype TSX-401R; Canon Medical Systems) [6, 7], respectively. These chest scans in the two positions were unenhanced and performed during both deep inspiration and expiration breath-holds with automatic exposure control using a noise index of 24 HU for a slice thickness of 5 mm (tube current range, 10–350 mA). Other scanning parameters were also the same for the supine and upright chest CT scans: peak tube voltage, 120 kVp; rotation speed, 0.5 s; slice collimation, 0.5 mm × 80; and pitch factor, 0.813. The series of contiguous 0.5-mm-thick images was reconstructed with adaptive iterative dose reduction 3D (Canon Medical Systems) [13].

Pulmonary Function Tests
All participants underwent PFTs within 2 h on the same day that they underwent both conventional and upright CT examinations. PFTs were performed with the patient in a stable condition in the sitting position using a spirometer (Chestac-8900; Chest M.I., Tokyo, Japan), in accordance with American Thoracic Society/European Respiratory Society recommendations [14, 15]. Predicted values of spirometric measurements were derived from the guidelines of the Japanese Respiratory Society [16].

Lung, Lobe, and Airway Volume Measurements Using CT
Measurements of the lung, lobe, and airway volumes on both CT images of the 48 patients were performed by a chest radiologist with 15 years of experience using a commercially available workstation (Synapse Vincent; Fuji Film Co., Ltd., Tokyo, Japan) (Fig. 3) [7, 8, 12, 17–21]. This workstation incorporated a computer-aided detection system and automatically extracted the right and left lungs and the entire airway tree (from the trachea to all bilateral airways with lumen diameters of more than approximate-ly 1.5 mm), defined as the airway volume [7, 8, 12, 17–21]. The workstation recognized lobar bronchi and determined the locations of fissures. The chest radiologist verified the computer-aided segmentation results and made manual corrections by delineating fissures when the computer-aided detection system failed to identify them properly, as previously described [7, 8, 17, 18]. To assess intra-observer agreement, a second measurement of the first 20 patients was performed 2 months after the first assessment by the same radiologist. To assess inter-observer agreement, the measurements of the volumes of the first 20 patients were performed by the other radiologist with 6 years of experience. All measurements were performed in a randomized and blinded manner. During all measurements, the radiologists were also blinded to patient characteristics and PFT results. The ratios of inspiratory to expiratory volumes on CT and the ratios of volumes in the standing position to those in the supine position were also calculated.

Statistical Analysis
Data are presented as the mean ± standard deviation. The sample size calculation was based on postural changes in lung volume. The expected mean change in total lung volume (TLV) between the supine and standing positions was 400 mL, which was based on the postural change in a previous volunteer cohort [8], and we assumed the standard deviation of the change to be 830 mL. To detect clinically significant differences in CT-based volumes between the two positions with a significance level of 5% (two-tailed) and power of 90%, 48 patients were required. We estimated the dropout rate to be 5%; thus, the sample size was determined to be 51.

Paired t tests were performed to analyze the differences in the lung, lobe, and airway volumes and ratios of inspiratory to expiratory volumes between the supine and standing positions. The associations between CT volumes in each position and PFT measurements were evaluated using Pearson correlation coefficients. The difference in age between women and men was assessed using Student’s t test. Mann-Whitney U tests were performed to analyze
Fig. 3. Representative lung, lobe, and airway volume measurements in a 77-year-old male patient with COPD. **a** Axial images. **b** Sagittal images. **c** Coronal images. **d** Volume rendering lung/lobe images. **e** Volume rendering airway images acquired in the supine and standing positions. Yellow, right upper lobe; blue, right middle lobe; green, right lower lobe; pink, left upper lobe; and purple, left lower lobe. COPD, chronic obstructive pulmonary disease.


Results

Participant Characteristics

The clinical characteristics of the 48 participants (mean age, 76.2 ± 7.5 years; 44 men) are shown in Table 1. No significant difference in age was observed between women and men (81.8 ± 4.4 vs. 75.7 ± 7.5 years, \( p = 0.1208 \)).

| Demographic variables                        | Mean ± standard deviation or n | Range     |
|----------------------------------------------|-------------------------------|-----------|
| Age, years                                   | 76.2±7.5                      | 59–89     |
| Sex (female/male), n                         | 4/44                          | N.A.      |
| Height, cm                                   | 164.0±8.3                     | 144.9–181.0 |
| Weight, kg                                   | 63.8±12.2                     | 32.7–93.4 |
| Body mass index, kg/m²                       | 23.6±3.2                      | 14.8–30.7 |
| Smoking index (pack-years)                   | 57.7±38.2                     | 10–200    |
| PFT Vital capacity, L                        | 3.61±0.78                     | 1.62–4.80 |
| FVC, L                                        | 3.51±0.80                     | 1.59–4.76 |
| FVC (% predicted)                            | 108.2±15.2                    | 78.6–136.9 |
| FEV₁, L                                      | 1.78±0.63                     | 0.78–3.17 |
| FEV₁ (% predicted)                           | 68.9±19.1                     | 29.0–114.6 |
| FEV₁/FVC, %                                   | 50.6±12.6                     | 23.1–68.6 |
| Tidal volume, L                              | 0.74±0.17                     | 0.36–1.06 |
| Residual volume, L                           | 1.93±0.56                     | 1.09–3.57 |
| Residual volume (% predicted)                | 104.6±31.4                    | 53.6–189.9 |
| Functional residual capacity, L              | 3.22±0.70                     | 1.91–4.56 |
| Functional residual capacity (% predicted)   | 98.1±19.3                     | 56.5–140.3 |
| Total lung capacity, L                       | 5.53±0.99                     | 2.99–6.84 |
| Total lung capacity (% predicted)            | 103.1±12.9                    | 72.7–127.6 |
| Residual volume/total lung capacity, %       | 35.0±7.7                      | 24.0–53.2 |
| DLCO, mL/min/torrent                         | 15.0±5.7                      | 3.8–25.9  |
| DLCO (% predicted)                           | 98.8±30.9                     | 28.3–161.3 |
| GOLD (1/2/3/4), n                            | 14/27/6/1                    | N.A.      |

COPD, chronic obstructive pulmonary disease; DLCO, diffusing capacity for carbon monoxide; FEV₁, forced expiratory volume in 1 s; FVC, forced vital capacity; GOLD, global initiative for chronic obstructive lung disease; N.A., not applicable.

Association between CT Volumes and PFT Measurements

The correlation coefficients (\( r \)) between the TLVs on inspiratory CT in the supine/standing position and the PFT total lung capacity and vital capacity were 0.887/0.920 (Fig. 4a) and 0.711/0.781 (Fig. 4b), respectively. The correlation coefficients between the TLVs on expiratory CT in the supine/standing position and the PFT functional residual capacity and residual volume were 0.676/0.744 (Fig. 4c) and 0.713/0.739 (Fig. 4d), respectively. The coefficients between the airway volume on inspiratory CT in the supine/standing position and the PFT FEV₁ were 0.471/0.524, respectively (Fig. 4e).

Lung, Lobe, and Airway Volumes on CT in Supine and Standing Positions

The average inspiratory volumes of the total lung (4.0% increase), right lung (3.9% increase), right upper lobe (4.6% increase), right lower lobe (6.9% increase), left lung (4.2% increase), left upper lobe (3.6% increase), left
lower lobe (5.0% increase), and airway (4.6% increase) were significantly higher in the standing position than in the supine position (all \( p < 0.005 \)) (Table 2). Additionally, the average expiratory volumes of the total lung (5.0% increase), right lung (5.7% increase), right upper lobe (15.5% increase), right lower lobe (6.1% increase), left lung (4.2% increase), left upper lobe (5.7% increase), and airway (21.2% increase) were significantly higher in the standing position than in the supine position (all \( p < 0.05 \)) (Table 2). Conversely, the inspiratory and expiratory right middle lobe volumes were significantly lower in the standing position than in the supine position (4.6% and 15.9% decreases, respectively, both \( p < 0.001 \)). No significant difference was found in the expiratory left lower lobe volume between the two positions (\( p = 0.4836 \)).

The average rates of decrease in airway volume from the standing position to the supine position on inspiratory and expiratory CTs were −4.4% and −17.5%, respectively. The average rates of decrease in airway volume from inspiration to expiration in the supine and standing positions were −36.9% and −26.9%, respectively.

**Ratio of Inspiratory Volume to Expiratory Volume in Supine and Standing Positions**

The ratio of inspiratory volume to expiratory volume of the right middle lobe was significantly higher in the standing position than in the supine position (\( p < 0.0001 \)); however, the ratios of inspiratory volumes to expiratory volumes of the right upper lobe and airway were significantly lower in the standing position than in the supine position (all \( p < 0.0001 \)) (Table 3). No significant differences were observed in the ratio of inspiratory volume to expiratory volume of the total lung, right lung, right lower lobe, left lung, left upper lobe, and left lower lobe between the supine and standing positions (Table 3).

**Fig. 4.** Associations between CT volumes and pulmonary function test measurements. Scatterplots show the associations between (a) the total lung volumes (TLVs) on inspiratory CT in the supine/standing position and the PFT total lung capacity, (b) the TLVs on inspiratory CT in the supine/standing position and the PFT vital capacity, (c) the TLVs on expiratory CT in the supine/standing position and the PFT functional residual capacity, (d) the TLVs on expiratory CT in the supine/standing position and the PFT residual volume, and (e) the airway volumes on inspiratory CT in the supine/standing position and the PFT FEV1. Dotted lines show estimated regression. CT, computed tomography; FEV1, forced expiratory volume in 1 s; PFT, pulmonary function test.
Ratio of Volume in Standing Position to Volume in Supine Position: GOLD 1 versus GOLD 2, 3, and 4

No significant differences were found in age, sex, height, weight, and body mass index between the GOLD 1 and GOLD 2–4 groups (online suppl. Table 1; see www.karger.com/doi/10.1159/000527067 for all online suppl. material). The ratios of the volumes in the standing position to those in the supine position of the inspiratory total lung, right lung, and left lung were significantly higher in the GOLD 1 group than in the GOLD 2–4 groups (all p < 0.03) (Table 4). No significant differences were found between the GOLD 1 and 2–4 groups in the ratios of the volumes in the standing position to those in the supine position of the expiratory total lung, right lung, left lung, all lobes, and airway (Table 4).

| Table 2. | Inspiratory and expiratory lung, lobe, and airway volumes on CT in the supine and standing positions (48 patients with COPD) |
|---------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| **Volume on CT, mean ± standard deviation (range)** | **p value** | **Average increase or decrease, %** | **supine versus standing** |
| supine, mL | standing, mL |  |  |
| Total (bilateral lung (inspiratory)) | 5,336.5±1,053.3 (3,003.2–7,583.1) | 5,550.9±1,061.9 (3,086.0–7,500.7) | <0.0001 | +4.0 |
| Right lung (inspiratory) | 2,879.4±581.2 (1,466.1–3,919.3) | 2,990.7±595.3 (1,568.5–3,913.9) | <0.0001 | +4.6 |
| Right upper lobe (inspiratory) | 1,186.8±345.9 (405.3–2,060.1) | 1,241.9±364.0 (379.9–2,064.3) | <0.0001 | +4.6 |
| Right middle lobe (inspiratory) | 523.6±203.0 (3.8–1,229.8) | 499.3±202.5 (2.0–1,263.5) | 0.0002 | −4.6 |
| Right lower lobe (inspiratory) | 1,169.0±369.2 (326.7–2,031.8) | 1,249.5±380.0 (351.8–2,109.3) | <0.0001 | +6.9 |
| Left lung (inspiratory) | 2,457.1±534.5 (1,385.2–3,663.8) | 2,560.2±520.4 (1,434.3–3,586.9) | 0.0003 | +4.2 |
| Left upper lobe (inspiratory) | 1,430.4±289.7 (853.6–2,013.0) | 1,482.4±304.3 (872.4–2,093.2) | 0.0006 | +3.6 |
| Left lower lobe (inspiratory) | 1,026.6±376.1 (87.3–1,925.8) | 1,077.9±365.7 (86.7–1,873.8) | 0.0046 | +5.0 |
| Airway (inspiratory) | 88.3±18.9 (46.8–137.0) | 92.4±18.5 (52.1–143.1) | <0.0001 | +4.6 |
| Total (bilateral lung (expiratory)) | 3,543.0±955.1 (1,997.1–5,799.7) | 3,719.0±1,013.4 (2,131.6–5,938.6) | 0.0049 | +5.0 |
| Right lung (expiratory) | 1,919.8±514.7 (804.5–3,031.6) | 2,027.4±575.5 (818.3–3,466.5) | 0.0008 | +5.7 |
| Right upper lobe (expiratory) | 822.0±285.8 (253.4–1,621.0) | 949.7±313.8 (304.8–1,900.3) | <0.0001 | +15.5 |
| Right middle lobe (expiratory) | 391.9±159.5 (3.9–920.4) | 329.7±150.0 (1.4–789.4) | <0.0001 | −15.9 |
| Right lower lobe (expiratory) | 705.0±288.2 (156.2–1,527.2) | 747.9±288.0 (146.5–1,550.0) | 0.0136 | +6.1 |
| Left lung (expiratory) | 1,624.0±478.6 (962.8–3,045.7) | 1,691.6±465.6 (964.0–2,941.3) | 0.0422 | +4.2 |
| Left upper lobe (expiratory) | 1,005.3±271.6 (600.4–1,710.1) | 1,062.5±279.4 (386.2–1,920.1) | 0.0069 | +5.7 |
| Left lower lobe (expiratory) | 618.7±295.0 (78.6–1,722.4) | 629.1±278.2 (73.4–1,668.7) | 0.4836 | +1.7 |
| Airway (expiratory) | 55.7±12.9 (19.6–79.7) | 67.5±14.9 (37.6–112.4) | <0.0001 | +21.2 |

COPD, chronic obstructive pulmonary disease; CT, computed tomography.

| Table 3. | Ratio of inspiratory volume to expiratory volume on CT in the supine and standing positions (48 patients with COPD) |
|---------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| **Ratio of inspiratory volume to expiratory volume on CT, mean ± standard deviation (range)** | **p value** | **Average increase or decrease, %** | **supine versus standing** |
| supine | standing |  |  |
| Total (bilateral lung) | 1.543±0.213 (1.185–1.981) | 1.539±0.251 (1.004–2.037) | 0.8982 |
| Right lung | 1.536±0.208 (1.176–1.988) | 1.523±0.244 (0.996–2.026) | 0.6113 |
| Right upper lobe | 1.481±0.194 (1.193–1.865) | 1.328±0.162 (1.026–1.717) | <0.0001 |
| Right middle lobe | 1.349±0.195 (0.965–1.847) | 1.590±0.381 (0.849–2.544) | <0.0001 |
| Right lower lobe | 1.742±0.366 (1.161–2.922) | 1.766±0.414 (0.977–2.921) | 0.5486 |
| Left lung | 1.553±0.232 (1.185–2.004) | 1.559±0.263 (1.015–2.066) | 0.8167 |
| Left upper lobe | 1.454±0.178 (1.151–1.790) | 1.426±0.198 (1.033–1.809) | 0.2713 |
| Left lower lobe | 1.729±0.385 (1.111–2.712) | 1.802±0.448 (0.984–2.726) | 0.1080 |
| Airway | 1.625±0.310 (1.101–2.676) | 1.390±0.217 (1.032–2.228) | <0.0001 |

COPD, chronic obstructive pulmonary disease; CT, computed tomography.
Inter-Observer and Intra-Observer Agreements

Inter- and intra-observer agreements (intra-class correlation coefficients) for measurements of CT volumes were 0.967–1.000 and 0.999–1.000, respectively.

Discussion

This prospective study demonstrated that upright CT-based lung and airway volumes were more strongly correlated with PFT measurements than supine CT-based volumes in patients with COPD. This may be because PFTs are conducted in the upright position, and the direction of the thorax in PFTs corresponds to that in the upright CT rather than that in the conventional supine CT. Currently, no individual alternative is sufficient to replace conventional PFTs in all patients [5, 22]. However, our results suggest that, in addition to morphological evaluation of the chest, upright CT might be an alternative tool for predicting PFT measurements, such as total lung capacity, vital capacity, functional residual capacity, residual volume, and FEV1, in patients with COPD especially in situations where PFT cannot be performed. Upright CT could be a more accurate predictor of PFT measurements than conventional supine CT.

This study also demonstrated that the inspiratory volumes of the bilateral upper lobes, lower lobes, and lungs were significantly higher in the standing position than in the supine position, with the lower lobes exhibiting relatively greater changes. However, the inspiratory right middle lobe volume was significantly lower in the standing position than in the supine position. COPD seems to increase the risk of developing lung cancer [23, 24], and our findings would be important given their potential impact on preoperative CT volumetry of the lung and lobe in patients with COPD who have been diagnosed with lung cancer. Upright CT provides images of daily life postures and may be useful for a relatively more accurate prelobectomy (especially in lobectomy of the right middle lobe) prediction of postoperative residual pulmonary function in these patients. The reason for the lower inspiratory/expiratory right middle lobe volume in the standing position compared with that in the supine position is not immediately clear; however, the right middle lobe has a relatively small volume and is located in a relatively inferior and anterior portion of the right lung in the standing position. Therefore, the right middle lobe may be
compressed by enlarged upper and lower lobes in the standing position, with volumes 2–3 times larger than that of the middle lobe [7].

In our study, patients with COPD exhibited average rates of increase in inspiratory and expiratory airway volumes from the supine to the standing position of 4.6% and 21.2%, respectively. In other words, the average rate of decrease in airway volume from the standing to the supine position on expiratory CT was larger than that on inspiratory CT (−17.5 vs. −4.4%). Furthermore, the average rate of decrease in airway volume from inspiration to expiration was larger in the supine position than in the standing position (−36.9 vs. −26.9%). In patients with COPD, breathing discomfort can become further amplified through adoption of the supine position (i.e., orthopnea) [25, 26]. In many individuals with COPD, orthopnea can be a problem at night and can disrupt sleep; however, the precise mechanisms underlying orthopnea remain unknown [26]. Eltayara et al. [25] reported that increased airway resistance in the supine position due to a lower end-expiratory lung volume probably plays a role in the genesis of orthopnea. Considering our results, the increased airway resistance in the supine position due to a lower expiratory airway volume could also play a role in the genesis of orthopnea.

Previous studies have compared lung volumes between the supine and standing positions in a volunteer cohort without any symptoms [7, 8]. They reported that the average percentage increase in the TLV in the standing position compared with that in the supine position was approximately 10%. This is numerically higher than that in the current COPD cohort (4%). Additionally, our results showed that the increase in the TLV in the standing position compared with that in the supine position in patients with mild COPD (GOLD 1) was significantly greater than that in patients with moderate and severe COPD (GOLD 2–4) (7 vs. 3%). This may be because of the loss of diaphragmatic mobility in patients with COPD [27].

There were some limitations to our study. First, we included only 48 patients (predominantly male, 92%) from a single institution with a relatively lower percentage of patients with severe COPD (only 13% were GOLD 3 and 2% were GOLD 4). Therefore, additional multi-center studies with a large population, containing an appropriate number of women and a representative percentage of patients with severe COPD, are needed to confirm our preliminary results. Second, although the observers independently assessed the CT images in a randomized and blinded manner, they could recognize patients’ positions to some extent because of the absence or existence of CT tables. However, the volume measurements were semi-automatic due to the use of a commercially available workstation; thus, observer bias would have been nonsignificant. In addition, the inter- and intra-observer agreements (intra-class correlation coefficients) in this study were high (>0.96). Third, we performed the PFTs in the upright position but not in the supine position; therefore, we could not evaluate the correlations between the volumes on supine CT and measurements on supine PFT. Fourth, in this study, upright CT was performed with arms lowered, whereas conventional supine CT was performed with arms raised; thus, the form of the chest would have been slightly different between upright and supine positions, which may have influenced the results of this study. However, we believe that standing with the arms lowered is the natural standing posture for humans.

**Conclusion**

Upright CT-based lung and airway volumes were more correlated with PFT measurements than supine CT-based volumes in patients with COPD. Thus, upright CT may be a relatively more reliable alternative tool for predicting PFT measurements when PFTs cannot be performed. The inspiratory and expiratory bilateral upper lobes, right lower lobe, right lung, left lung, and airway volumes were significantly higher in the standing position than in the supine position; however, the inspiratory and expiratory right middle lobe volumes were significantly lower in the standing position. Our findings indicate that upright CT may be more reliable than supine CT for pre-lobectomy predictions of postoperative residual pulmonary function in patients with COPD who have been diagnosed with lung cancer.

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**Statement of Ethics**

This study was conducted in accordance with the amended Declaration of Helsinki. This study protocol was reviewed and approved by Keio University School of Medicine Ethics Committee, approval number 20160385. Written informed consent was obtained from all participants.
Conflict of Interest Statement

Masahiro Jinzaki has received a grant from Canon Medical Systems. However, Canon Medical Systems was not involved in the design and conduct of the study, in the collection, analysis, and interpretation of the data, or in the preparation, review, and approval of the manuscript. The remaining authors have no conflicts of interest to declare.

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Author Contributions

Yoshitake Yamada, Shotaro Chubachi, and Masahiro Jinzaki were responsible for the conception or design of the work; Yoshitake Yamada, Shotaro Chubachi, Minoru Yamada, Yoichi Yokoyama, Akiko Tanabe, Shihoko Matsuoka, and Yuki Niiijima were responsible for the acquisition of data; Yoshitake Yamada, Shotaro Chubachi, Minoru Yamada, and Yoichi Yokoyama analyzed and interpreted the data; Yoshitake Yamada, Shotaro Chubachi, Minoru Yamada, Yoichi Yokoyama, Akiko Tanabe, Shihoko Matsuoka, Yuki Niiijima, Mitsuru Murata, Koichi Fukunaga, and Masahiro Jinzaki drafted or revised the paper for important intellectual content and final approval of data.

Data Availability Statement

All data generated or analyzed during this study are included in this article and its online supplementary material. Further inquiries can be directed to the corresponding author.

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