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ORIGINAL RESEARCH

Influence of Emphysema and Air Trapping Heterogeneity on Pulmonary Function in Patients with COPD

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Purpose: To explore the influence of emphysema and air trapping heterogeneity on pulmonary function changes in patients with stable chronic obstructive pulmonary disease (COPD).

Patients and methods: One hundred and seventy-nine patients with stable COPD were enrolled in this prospective study. All patients underwent low-dose inspiratory and expiratory CT scanning and pulmonary-function tests. CT quantitative data for the emphysema index (EI) on full-inspiration and air trapping (AT) on full-expiration were measured for the whole lung, the right and left lungs, and the cranial-caudal lung zones. The heterogeneity index (HI) values for emphysema and air trapping were determined as the ratio of the difference to the sum of the respective indexes. The cranial-caudal HI and left–right lung HI were compared between mild-to-moderate (GOLD stage I and II) and severe (GOLD stage III and IV) disease groups. The associations between HI and pulmonary-function measurements adjusted for age, sex, height, smoking history, EI and AT of the total lung were assessed using multiple linear regression analysis.

Results: The absolute values for cranial-caudal HI (AT CC HI) and left–right lung HI (AT_LR_HI) on full-expiration were significantly larger in the mild-to-moderate group, while no significant intergroup differences were observed on full-inspiration. COPD patients with lower-zone and/or left-lung predominance showed significantly lower pulmonary function than those with upper-zone and/or right-lung predominance on full-expiration, whereas no significant differences were observed on full-inspiration. The absolute values of AT_CC_HI and AT_LR_HI significantly correlated with pulmonary-function measurements. Higher AT_CC_HI and lower AT_LR_HI absolute values indicated better pulmonary function, after adjusting for age, sex, height, smoking history, EI and AT of the total lung.

Conclusion: Subjects with more heterogeneous distribution and/or upper-zone predominant and/or right-lung predominant patterns on full-expiration tend to have better pulmonary function. Thus, in comparison with emphysema heterogeneity, AT heterogeneity better reflects the pulmonary function changes in COPD patients.

Keywords: pulmonary disease, chronic obstructive, small airway disease, heterogeneous distribution, tomography, X-Ray computed

Introduction

Chronic obstructive pulmonary disease (COPD) is defined by the presence of airflow obstruction that is "not fully reversible".^{[1](#page-8-0)} Pulmonary emphysema and airway lesions are the main pathological changes in patients with COPD. Emphysema in COPD patients shows considerable heterogeneity in its extent and spatial distribution, 2 and the heterogeneity in the distribution of emphysema might be

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associated with the clinical severity of the disease.^{[3](#page-8-2)–[6](#page-8-3)} As a result, the importance of emphysema distribution in COPD assessment has been widely recognized. Accurate phenotyping of emphysema distribution might be useful in predicting disease progression and prognosis and designing effective personalized therapeutic or management protocols for preventing disease progression.[7](#page-8-4)

To date, spirometry remains the primary method for diagnosis and monitoring of COPD. However, traditional pulmonary-function tests (PFTs) have a low sensitivity for diagnosing early-stage COPD, since 30% of the patients may suffer from emphysema before exhibiting any detectable decline in pulmonary function[.8](#page-8-5) Furthermore, abnormalities in regional function and morphology cannot be evaluated by PFTs. As an alternative to PFTs, CT examinations offer substantial advantages in the assessment of regional destruction of pulmonary parenchyma and airway remodeling. Advances in CT scanning and image-processing software have allowed precise measurement of the extent and heterogeneity of emphysema and air trapping (AT), which may correlate with functional changes.

Several previous studies have focussed on the effect of the cranial-caudal emphysema heterogeneity on pulmonary function on full-inspiration, but their results were not completely consistent.^{[7,](#page-8-4)[9](#page-8-6)–[11](#page-8-7)} The heterogeneity in the distribution in the left and right lungs in patients with COPD was seldom reported. Furthermore, the effect of AT heterogeneity on pulmonary function on full-expiration has not been fully discussed.

Small airway lesions are known to be the main factors leading to irreversible airflow limitation in COPD patients. Expiratory flow limitation is the pathophysiologic hallmark of these patients. Small airway lesions can be indir-ectly assessed by measurement of AT on expiration.^{[12](#page-8-8)} Our previous study has shown that AT on full-expiration shows better correlation with pulmonary function in COPD patients.[13](#page-8-9) Therefore, we speculated that AT heterogeneity may be more advantageous in reflecting pulmonary function. To test this hypothesis, our study aimed to evaluate the influence of the heterogeneity distribution on pulmonary-function parameters by using inspiratory-to-expiratory CT scans in COPD patients.

Materials and Methods **Subjects**

The protocol for this prospective clinical study was approved by the Human Research Ethics Board of Beijing Chao-Yang Hospital (study 2016-KE-183-1) and conducted in accordance with the Declaration of Helsinki. A signed written informed consent document was obtained from each patient prior to participation.

The study population was randomly selected from the Department of Pulmonary and Critical Care Medicine outpatients at our hospital between June 2016 and June 2018 by using the following inclusion criteria: (1) age 40–75 years; (2) a history of chronic respiratory symptoms, including wheeze, cough, expectoration, and dyspnea; and (3) pre-bronchodilator (pre-BD) forced expiratory volume in 1 second $(FEV_1)/$ forced vital capacity (FVC) ratio <70%. Subjects were excluded if they met any of the following criteria: (1) post-bronchodilator (post-BD) $FEV₁$ /FVC ratio $\geq 70\%$; (2) unable to cooperate with respiration; (3) presence of congenital heart disease or congestive heart failure; or (4) presence of severe pulmonary lesions or dysplasia. A total of 179 patients were eventually selected on the basis of these criteria and divided into mild-tomoderate and severe groups (GOLD stage I and II vs GOLD stage III and IV). Both CT scanning and PFTs were performed post-BD (salbutamol) administration.

CT Protocols

All patients were scanned in the supine position with a 64- MDCTsystem (Light Speed VCT, GE Healthcare, Milwaukee, WI, USA) that was calibrated routinely. The patients received thorough pre-scan instructions and were carefully followed up to guarantee full-inspiration and full-expiration levels for the CT examinations. The scans were obtained with the following parameters: tube voltage, 120 kV; tube current, 50 mAs; pitch, 1.0; and field of view, 280 to 350 mm. The images were acquired from the lung apices to the bases without the use of intravenous contrast and were reconstructed with a 1.25-mm reconstruction slice thickness and 1.25-mm interval using a standard algorithm. After post-BD administration of salbutamol (Ventolin Aerosol; 400 μg, GlaxoSmithKline), PFT was performed within 30 min and CT scanning was performed within 90 min.

CT Densitometry

All CT images were analyzed using the GE ADW 4.5 densitometry workstation (Thoracic-VCAR; GE Healthcare), which automatically extracts lung segments. The trachea and the main bronchi were also eliminated. Manual modification was performed if necessary to correct extraction errors for lung regions. Emphysema index (EI) was quantified as the percentage of lung voxels with attenuation lower

than –950 HU on full-inspiration. AT was defined as the percentage of lung voxels with a CT attenuation value below −856 HU on full-expiration. EI and AT for the right lung, left lung, and whole lung were measured. The right and left lungs were then divided into the upper zone, middle zone, and lower zone, based on the level of the carina and the inferior right pulmonary vein. The EI and AT of each zone were also measured.

The absolute value of the cranial-caudal heterogeneity index on full-inspiration (EI_CC_HI) or on full-expiration (AT_CC_HI) between the upper and lower zones was computed Eq. (1,2). Similarly, the absolute value of the heterogeneity index (HI) between the left–right lungs on fullinspiration (EI_LR_HI) or on full-expiration (AT_LR_HI) was computed Eq. $(3,4)$. EI_{upper} (AT_{upper}) was the percentage of emphysema (AT) voxels as the sum of that in left upper, right upper, left middle, and right middle zones, while EI_{lower} (AT_{lower}) was the percentage of emphysema (AT) voxels as the sum of that in left lower and right lower zones. A higher absolute value of the HI represented a more heterogeneous distribution of emphysema or AT, and a lower absolute value of the HI represented a homogeneous distribution.

$$
ELCC_HI = (EL_{upper} - EI_{lower}) / (EI_{upper} + EI_{lower}) \times 100\%
$$
\n(1)

$$
AT_CC_HI = (AT_{upper} - AT_{lower}) / (AT_{upper} + AT_{lower}) \times 100\%
$$
\n(2)

$$
E1_LR_HI = (EIleft - EIright)/(EIleft + EIright) \times 100\% (3)
$$

AT L.R.HI =
$$
(AT_{left} - AT_{right}) / (AT_{left} + AT_{right}) \times 100\%
$$

(4)

PFT Technique

Pulmonary function was assessed via spirometry and plethysmography (Jaeger MasterScreen; Viasys Healthcare, Höchberg, Germany) according to European Respiratory Society (ERS)/American Thoracic Society (ATS) Guide-lines.^{[14](#page-8-10)} For each subject, the following functional parameters were assessed post-BD: FEV_1 , FVC , the FEV_1 /FVC ratio, the FEV₁% predicted (FEV₁(%pred)), and the inspiratory capacity (IC)/total lung capacity (TLC). The PFT parameters of COPD patients are summarized in [Table 1](#page-2-0). The modified British medical research council (mMRC) score, COPD assessment test (CAT) score, and number of COPD acute exacerbations in the past year (N_{1AE}) were also recorded [\(Table 1](#page-2-0)).

Table 1 Patient Characteristics

| Parameter | $N=179$ |
|---|--------------------------------------|
| Age, years | 64 (60, 69) |
| Sex: male: female | 156 (87.2%)/23 (12.8%) |
| Height | 1.67 (1.63, 1.72) |
| BMI | 24.38±3.25 |
| Smoking status, current: former: never | 57 (31.8%)/103 (57.5%)/19 (10.6%) |
| Pack-years | 34.5 (18.5, 46.75) |
| $FEV1$ (L) | 1.52 (1.11, 2.00) |
| FEV ₁ (%pred) | 56% (41%, 71%) |
| FVC (L), mean ±SD | 3.07 ± 0.74 |
| FEV ₁ /FVC | 49% (42%, 61%) |
| IC/TLC | 24% (17%, 33%) |
| CAT | 13(8, 18) |
| mMRC | 1(1, 2) |
| N_{IAF} | 0(0, 1) |
| GOLD | |
| Mild-to-moderate | 105 (58.7%) |
| Severe | 74 (41.3%) |
| El of the total lung | 13.11(5.36, 22.21) |
| AT of the total lung | 53.74 (36.88, 65.72) |
| Absolute value of El_CC_HI | 19.04 (9.40, 31.78) |
| Absolute value of AT CC HI | 9.76 (3.50, 19.58) |
| Absolute value of El LR HI | 10.42 (4.84, 19.46) |
| Absolute value of AT_LR_HI | 4.44 (1.58, 9.75) |

Note: Values are presented as mean \pm SD, n (%) or median (interquartile range). Abbreviations: BMI, body mass index; FEV₁, forced expiratory volume in 1 second; FEV₁(%pred), the FEV₁% predicted; FVC, forced vital capacity; IC/TLC, inspiratory capacity/total lung capacity; CAT, COPD assessment test; mMRC, modified British Medical Research Council; N_{1AE} , number of COPD acute exacerbations in the past year.

Statistical Analyses

All statistical analyses were performed with the SPSS statistical software package, version 21.0 (IBM Corporation, Armonk, NY, USA). K-means clustering data-driven analysis was performed on the HI to divide subjects into two groups of subtypes: upper-zone-predominant and lowerzone-predominant emphysema (AT) subtypes as well as leftlung-predominant and right-lung-predominant emphysema (AT) subtypes. The intergroup differences were evaluated with Student's t test or the Mann–Whitney U -test when the data did not pass the normality test (Shapiro–Wilk test). Spearman rank correlation analysis was used to determine the association between pairs of variables for non-parametric data. Associations between the absolute value of the HI and the lung function measures, including FEV_1 , $FEV_1(\% pred)$, $FVC, FEV₁/FVC, and IC/TLC, were assessed by using mul$ tiple linear regression analysis after adjusting for age, sex, height, smoking history (pack-years), and EI and AT of the total lung. P values below 0.05 (two-tailed) were considered statistically significant.

Results

The demographic, imaging, clinical, and PFT parameters in participants with COPD are shown in [Table 1](#page-2-0). On fullexpiration, the absolute values of AT_CC_HI and AT_LR_HI showed significant intergroup differences. Subjects with a more homogeneous distribution of AT had poorer lung function than those showing a heterogeneous distribution. On fullinspiration, the absolute values of EI_CC_HI and EI_LR_HI showed no significant intergroup differences [\(Table 2](#page-3-0), [Figure 1A](#page-4-0)–[D](#page-4-0), [Figure 2A](#page-4-1)–[D\)](#page-4-1).

On full-expiration, the COPD patients with lower-zone and/or left-lung-predominant AT showed significantly lower pulmonary function than the patients with upperzone and/or right-lung-predominant AT. There were no statistically significant differences in pulmonary function between lower-zone and upper-zone predominance and between left-lung and right-lung predominance on fullinspiration [\(Tables 3](#page-5-0) and [4\)](#page-5-1).

Correlation between the absolute values of EI_CC_HI, AT_CC_HI, EI_LR_HI or AT_LR_HI and the PFT results is analysed. The absolute value of AT_CC_HI was significantly positively associated with $FEV_1 (r = 0.374, p < 0.001)$, FEV_1 (%pred) $(r = 0.333, p \le 0.001)$, FVC $(r = 0.268, p \le 0.001)$, FEV₁/FVC ($r = 0.346$, $p < 0.001$), and IC/TLC ($r = 0.269$, $p \le 0.01$) [\(Figure 3A](#page-6-0)–[E](#page-6-0)). The absolute value of AT LR HI was positively associated with FEV_1 (r = 0.149, p < 0.05), FEV₁(%pred) (r = 0.167, p < 0.05), and IC/TLC (r = 0.224, p < 0.05), whereas, no correlation was observed between the absolute value of AT_LR_HI and FVC or FEV_1/FVC . There was no correlation between the absolute values of EI_CC_HI and EI_LR_HI and the PFT results. Multivariate linear regression analysis showed that a higher absolute value of AT_CC_HI and lower absolute value of AT_LR_HI indicated better pulmonary function. In contrast, the absolute values of EI CC HI and EI LR HI were not included in the model, after adjusting for age, sex, height, smoking history (packyears), and EI and AT of the total lung [\(Table 5\)](#page-7-0).

Discussion

We comprehensively studied cranial-caudal and left–right lung heterogeneity in COPD patients by using inspiratory-toexpiratory CT. The findings of this study showed that the heterogeneity in the distribution of AT correlated with pulmonary function changes, which may be helpful in understanding the development of airflow limitation in COPD patients.

In our study, subjects with a more homogeneous distribution of air trapping had worse lung function than those showing a heterogeneous distribution on full-expiration CT, whereas the absolute value of EI_CC_HI showed no significant intergroup difference on full-inspiration. This finding is consistent with a previous study in which there were no statistical differences in emphysema distributions for different clinical or physiologic parameters. 9 Some studies^{[10](#page-8-11)[,11](#page-8-7)[,15](#page-8-12),[16](#page-8-13)} have shown that patients with more homogeneous emphysema distribution have worse lung function on full-inspiration. This may be related to the different proportions of patients under GOLD classifications in the study group. Our results suggest that AT heterogeneity on full-expiration better reflects pulmonary function than emphysema heterogeneity on full-inspiration, which is rarely

Table 2 Comparison of the Absolute Values of HI Between Patients with Mild-to-Moderate and Severe Disease (GOLD Stage I and II vs GOLD Stage III and IV)

| CT | Mild-to-Moderate N=105 | Severe N=74 | P-Value |
|----------------------------|------------------------|----------------------|---------|
| Absolute value of El CC HI | 20.33 (8.30, 36.01) | 18.95 (11.08, 30.29) | >0.05 |
| Absolute value of AT CC HI | 12.69 (4.82, 23.94) | 6.50 (2.36, 12.72) | < 0.001 |
| Absolute value of El LR HI | 9.55(3.49, 19.53) | 10.66(6.43, 17.96) | >0.05 |
| Absolute value of AT LR HI | 5.38 (1.94, 12.11) | 3.33 (1.32, 6.43) | < 0.05 |

Note: Values are presented as median (interquartile range).

Abbreviations: Absolute value of El_CC_HI, absolute value of the cranial-caudal heterogeneity index on full-inspiration; Absolute value of AT_CC_HI, absolute value of the cranial-caudal heterogeneity index on full-expiration; Absolute value of El LR HI, absolute value of the heterogeneity index between the left-right lungs on fullinspiration; Absolute value of AT_LR_HI, absolute value of the heterogeneity index between the left–right lungs on full-expiration.

Figure 1 An example of air trapping heterogeneous distribution on full-expiration (A–D). The blue colored areas showed pixels of <-856 HU, suggestive of air trapping. (A,B) which were the different coronal slices of the same patients (not same with C,D) showed a heterogeneous distribution of AT. (A_1, A_2) were the same coronal slice and (B_1, B_2) were the same coronal slice. FEV₁ (L)= 2.18, FEV₁(%pred)= 71%, FVC (L)= 3.67, FEV₁/FVC= 59%, IC/TLC= 40%. (C,D) which were the different coronal slices of the same patients showed a homogeneous distribution of AT. (C_1, C_2) were the same coronal slice and (D_1, D_2) were the same coronal slice. FEV₁ (L) = 0.74, FEV₁ (%pred) = 30%, FVC (L) = 2.16, FEV₁ /FVC= 34%, IC/TLC= 20%.

Abbreviations: FEV₁, forced expiratory volume in 1 second; FEV₁(%pred), the FEV₁% predicted; FVC, forced vital capacity; IC/TLC, inspiratory capacity/total lung capacity.

Figure 2 An example of emphysema heterogeneous distribution on full-inspiration (A–D). The blue colored area showed pixels of <-950HU, suggestive of emphysema. (A, B) were the different coronal slices of the same patients (not same with C,D). (A₁,A₂) were the same coronal slice and (B₁,B₂) were the same coronal slice. FEV₁ (L)= 2.18, $FEV_1(\% pred) = 71\%$, FVC (L)= 3.67, FEV₁/FVC= 59%, IC/TLC= 40%. (C,D) were the different coronal slices of the same patients. (C₁,C₂) were the same coronal slice and (D_1,D_2) were the same coronal slice. FEV₁ (L)= 0.74, FEV₁(%pred)= 30%, FVC (L)= 2.16, FEV₁/FVC= 34%, IC/TLC= 20%.

Abbreviations: FEV₁, forced expiratory volume in 1 second; FEV₁(%pred), the FEV₁% predicted; FVC, forced vital capacity; IC/TLC: inspiratory capacity/total lung capacity.

| | | Upper-Zone Predominant Cluster | Lower-Zone Predominant Cluster | P-Value |
|----|--------------------------|---------------------------------------|---------------------------------------|---------|
| EI | n | 89 | 90 | |
| | FVC | 3.17 ± 0.75 | 2.96 ± 0.71 | 0.054 |
| | FEV ₁ | 1.65 (1.13, 2.09) | 1.39(1.05, 1.92) | 0.081 |
| | FEV ₁ /FVC | 0.50(0.43, 0.61) | 0.48 (0.42, 0.60) | 0.281 |
| | FEV ₁ (%pred) | 0.60 $(0.44, 0.78)$ | 0.55(0.39, 0.70) | 0.100 |
| | IC/TLC | 0.25 (0.18, 0.34) | 0.22 (0.16, 0.30) | 0.245 |
| AT | n | 67 | 112 | |
| | FVC | 3.33 ± 0.70 | 2.91 ± 0.71 | < 0.001 |
| | FEV, | 1.77 (1.38, 2.25) | 1.36(0.98, 1.79) | < 0.001 |
| | FEV ₁ /FVC | 0.56 (0.47, 0.63) | 0.46 (0.40, 0.58) | 0.001 |
| | FEV ₁ (%pred) | 0.65(0.47, 0.81) | 0.50(0.38, 0.69) | < 0.001 |
| | IC/TLC | 0.28 (0.19, 0.34) | 0.22 (0.15, 0.30) | 0.105 |

Table 3 A Comparison of PFT Parameters Between Patients with Upper-Zone and Lower-Zone Predominance

Note: Values are presented as mean ± SD or median (interquartile range).

Abbreviations: EI, emphysema index; AT, air trapping; FVC, forced vital capacity; FEV₁, forced expiratory volume in 1 second; FEV₁%pred), the FEV₁% predicted; IC/TLC, inspiratory capacity/total lung capacity.

Note: Values are presented as mean ± SD or median (interquartile range).

Abbreviations: El, emphysema index; AT, air trapping; FVC, forced vital capacity; FEV₁, forced expiratory volume in 1 second; FEV₁(%pred), the FEV₁% predicted; IC/TLC, inspiratory capacity/total lung capacity.

reported in the literature. A more heterogeneous distribution of emphysema and/or AT corresponds to relatively more residual normal lung parenchyma, better synchronization of respiratory movements that can be quantitatively assessed by strain measurement using dynamic-ventilation CT, and better pulmonary function.^{17[,18](#page-8-15)} In the early stage of small airway lesions, expiratory dysfunction manifests exclusively, while with the progression of disease, both inspiratory and expiratory functions show impairment. The structural changes in expiratory CT are consistent with the pulmonary functional changes.

Our study also showed that the absolute value of AT_LR_HI was significantly different between the two groups on fullexpiration, whereas the absolute values of EI_LR_HI showed no significant intergroup differences on full-inspiration, which was consistent with the literature.¹⁰ This result also confirmed our hypothesis that AT heterogeneity on full-expiration may be more valuable in reflecting pulmonary function.

The cranial-caudal heterogeneity of emphysema and/or AT distribution is an important predictor of the response to pulmonary function. However, there is little consensus regarding the definition of upper-zone-predominant and lower-zonepredominant emphysema and/or AT subtypes. Therefore, on the basis of HI, K-means clustering data-driven analysis was performed to divide the patients into upper-zone-predominant and lower-zone-predominant emphysema or AT subtypes with respect to cranial-caudal heterogeneity; and left-lung predominant and right-lung predominant subtypes between the left and right lungs. Previous studies^{3[,7](#page-8-4)[,9](#page-8-6),[19](#page-8-16)-[21](#page-8-17)} have shown that

Figure 3 The correlation between the absolute value of AT_CC_HI and pulmonary function. (A-E) showed the correlation between the absolute value of AT_CC_HI and PFT parameters, including FEV₁(A), FEV₁(%pred) (B), FVC (C), FEV₁/FVC (D) and IC/TLC (E).

Abbreviations: Absolute value of AT_CC_HI, absolute value of the cranial-caudal heterogeneity index on full-expiration; PFT, pulmonary function tests; FEV₁, forced expiratory volume in 1 second; FEV₁(%pred), the FEV₁% predicted; FVC, forced vital capacity; IC/TLC, inspiratory capacity/total lung capacity.

subjects with upper-zone predominance had better functional status on full-inspiration. Although the subjects showed no obvious differences in PFT parameters in the upper- versus lower-lung predominance on full-inspiration in our research, our study found the same results on full-expiration. Our study also found that subjects with right-lung-predominant AT had significantly better functional status than those with left-lungpredominant AT on full-expiration, whereas there were no statistically significant differences in pulmonary function on full-inspiration, which is consistent with the previous study.¹⁰ These results further confirm our hypothesis that AT heterogeneity on full-expiration may be more advantageous in reflecting pulmonary function. It is not easy to identify the exact factors underlying the variety in heterogeneous distribution among patients with COPD. On the basis of previous investigations, specific genes^{19[,20](#page-8-18)} (e.g., MMP-9, EPHX1, GSTP1) were found to be associated with distinct groups of subjects with upper lobe-predominant emphysema. Different etiologies may cause differences in the heterogeneous distribution. Early emphysema and AT may be located in the upper lung in patients with COPD caused by smoking, while early emphysema and AT caused by chronic bronchitis may begin in the lower lung. The COPD patients showing upper-zone dominant and/or right-lung-predominant distribution of AT had better pulmonary function, which may be related to the greater potential activity of the diaphragm. Lung hyperinflation has a major impact on the shape and position of the diaphragm due to the changes in the size of the lungs and chest, $2^{1,22}$ $2^{1,22}$ $2^{1,22}$ leading to diaphragmatic dysfunction, especially in lower-zone dominant and/or left-lung-predominant distribution. Our results may indicate that the airflow limitation in COPD patients develops from certain lung zones and/or one lung to the both lungs with disease progression. Furthermore, AT heterogeneity may provide a reference for estimating pulmonary function in COPD patients who are unable to cooperate with pulmonary function tests.

This study had several limitations. First, 179 subjects were enrolled with various degrees of disease severity, and patients classified as GOLD stage I (15.6%) and IV (6.7%) were limited. Second, as there are important sex-related differences in emphysema severity and distribution, the small proportion of participating women is a limitation of the present study. Additionally, the correlation between CT heterogeneity and clinical manifestations was not fully discussed in this study. Thus, future studies with larger sample sizes may yield more information about the heterogeneity of emphysema or AT via quantitative CT, as well as its correlation with clinical and functional changes.

Table 5 Multivariate Linear Regression Analysis Showing the Relationship Between CT Parameters and Pulmonary Function Parameters Table 5 Multivariate Linear Regression Analysis Showing the Relationship Between CT Parameters and Pulmonary Function Parameters

 $\mathrm{E}\subseteq\mathrm{C-H}$, absolute value of the cranial-causdal heterogeneity index on full-inspiration; Absolute value of $\mathrm{H}\subseteq\mathrm{C}\subseteq\mathrm{H}$, absolute value of the cranial-caudal heterogeneity index on full-inspiration; Absolute J. J, 디___Th, aosonue value or une craniar-aauar neuerogenely intex on iul-inspiration, Aosonue value or _______n, aosonue value or une craniar-audar neuerogenely intex on iuli-expiration, Aoso
of the heterogeneity index bet of the heterogeneity index between the left–right lungs on full-inspiration; Absolute value of AT_LR_HI, absolute value of the heterogeneity index between the left–right lungs on full-expiration.

Conclusion

In summary, subjects with more heterogeneous distribution and/or upper-zone-predominant and/or right-lungpredominant patterns on full-expiration tend to have better pulmonary function. Thus, in comparison with emphysema heterogeneity, AT heterogeneity better reflects the pulmonary function changes in COPD patients.

Author Contributions

All authors had full access to the study data, conducted the analysis, and take responsibility for the integrity of the data and the accuracy of the analysis. All authors contributed to drafting and revising the article, gave final approval of the version to be published, and agree to be accountable for all aspects of the work.

Disclosure

The authors report no conflicts of interest in this work.

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