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The regularity of anatomical variations of dominant pulmonary segments in the right upper lobe

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Abstract

Background: Anatomical variations often pose challenges to pulmonary surgery. Previous studies have mainly described the frequencies of bronchovascular anatomical variations in pulmonary segments, but did not determine the differences between pulmonary segments and the regularity behind these anatomical variations. Here, we attempted to investigate the regularity of bronchovascular anatomical variations in different pulmonary segments.

Methods: Thin-slice enhanced computed tomography data of 800 cases from our center were included in this study. Digitalized three-dimensional virtual lung segmentation was done, the dominant and inferior lung segments of the right upper lobe were defined, and the regularity of anatomical variations was explored.

Results: The mean volume ratio of the anterior segment of the right upper lobe (39.6 ± 8.6%) was highest, and that of the posterior segment (28.6 ± 7.9%) was lowest. Therefore, the dominant-type segment (DS + SDS) was dominant in the anterior segment, accounting for 74.6% (597/800), and the inferior-type segment (SIS + IS) was dominant in the posterior segment of the right upper lobe, accounting for 71.5% of cases (573/800). During the transformation of dominant and inferior lung segments, the corresponding regularity of anatomical variations could be displayed. For example, with an increase in the volume of the anterior segment of the right upper lobe, the occurrence rate of the bifurcated type of bronchus (B1 + 2, B3), the "central vein type" and the involvement of the trunk inferior and ascending artery in the blood supply of anterior segment gradually increased.

Conclusions: The existence of dominant segments will increase the diversity of anatomical variations and the complexity of pulmonary segmentectomy.

KEYWORDS
3D reconstruction, anatomical variations, dominant pulmonary segment, segmentectomy

INTRODUCTION

The development and wide application of high-resolution computed tomography (CT) has facilitated the increased detection of small pulmonary nodules in imaging studies,[1] thus providing a platform for the development of thoracoscopic sublobectomy, especially segmentectomy.[2]

Following the publication of the results of the clinical trial of JCOG0802,[3] the 5-year OS of segmentectomy was found to be higher than that of lobectomy for patients with pulmonary nodules with a diameter less than 2.0 cm and consolidation tumor ratio (CTR) greater than 0.50, proving

Zi-Hao Chen and Xiang-Peng Chu contributed equally to this work.

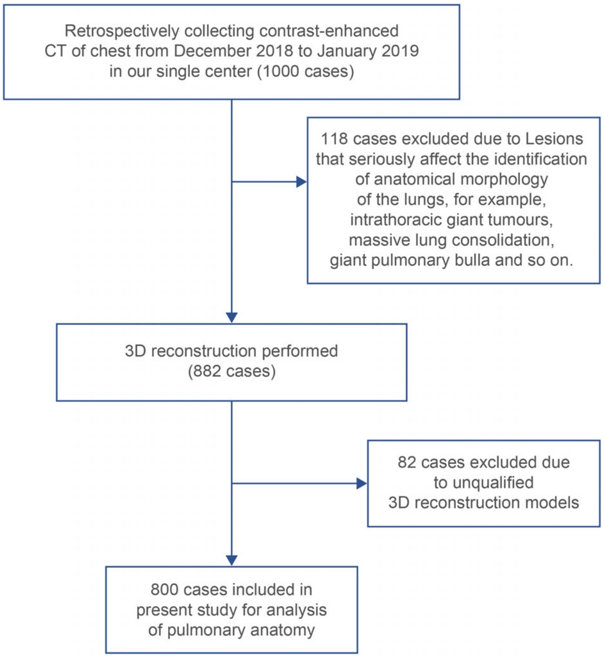

FIGURE 1 Schematic of the enrollment process

that segmentectomy is a safe and effective minimally invasive surgery, and the indications for segmentectomy have been further expanded.

However, in clinical practice, we have found that there are great individual differences between pulmonary segments, such as a large anterior segment in some people and a small anterior segment in others, thereby making it difficult to accurately identify the plane between segments and effectively guarantee the safe cutting edge. At the same time, we found that behind the differences of volume of lung segments, there are often variations in the anatomical structure within the lung segments, which brings some challenges to the safety of pulmonary segmentectomy.

Previous studies have analyzed and summarized the types and incidence of pulmonary anatomical variations,[4–9] but there have been no studies that have explored the differences in lung segment volume. Moreover, there is a lack of literature exploring the relationship between the differences of pulmonary segmental volume and the variations of anatomical structures.

We therefore attempted to use the three-dimensional (3D) reconstruction technique, which has been proven to be valuable in the preoperative assessment of anatomical segmentectomy,[10,11] to reconstruct stereoscopic images of pulmonary segments. In combination with the morphological measurement technique, we attempted to investigate the relationships between distribution differences of pulmonary segmental volume and the regularity of anatomical variations.

We selected the right upper lobe for this first report because more lobectomies and segmentectomies are performed than in other lobes.

TABLE 1 Characteristic of patients who underwent three dimensional lung reconstruction

Variable	N	%
Male	401	50.1
Female	399	49.9
Age	18–89 (median 54.7)	
Pneumonia	46	5.75
Pulmonary nodule	134	16.75
COPD	28	3.5
Thoracic deformity	0	0

METHODS

Patient preparation and examination

Between December 2018 and January 2019, 1000 patients who underwent contrast-enhanced CT of the chest were collected (Figure 1). The subjects came from the medical examination center of the Guangdong Provincial People's Hospital. The requirements of the study were that the patients were aged over 18 years old, and that thoracic deformity, chest trauma, intrathoracic giant tumors, massive lung consolidation, giant pulmonary bulla and other thoracic diseases had been eliminated. A total of 118 cases were excluded. Three-dimensional (3D) reconstruction was performed on 882 cases, of which 82 were excluded because the subsegmental branches of the pulmonary vessels were not adequately represented on 3D-CTAB. Finally, 800 consecutive cases (401 men and 399 women) were analyzed for variations of pulmonary anatomy. All enrolled patients were adults, and their mean age was 54.7 years (range: 18–89 years) (Table 1).

Reconstruction of 3D-CT angiography and bronchographic imaging

Before surgery, 1-mm thick contrast-enhanced CT slices were obtained, and high-resolution CT images were converted into Digital Imaging and Communications in Medicine data, which were input into a personal computer. Three-dimensional (3D) images were reproduced by volume rendering using an intelligent surgery planning platform (Perception Vision Medical Technologies Co., Ltd). The branching patterns of the bronchi, pulmonary arteries, and pulmonary veins were assessed with the 3D modeling shareware PVmed version 2.0 (https://isa.pvmedtech.com/).

Nomenclature of pulmonary bronchi, arteries, and veins

The branching patterns of the bronchi, pulmonary arteries, and pulmonary veins were named according to Nagashima's classification.[6]

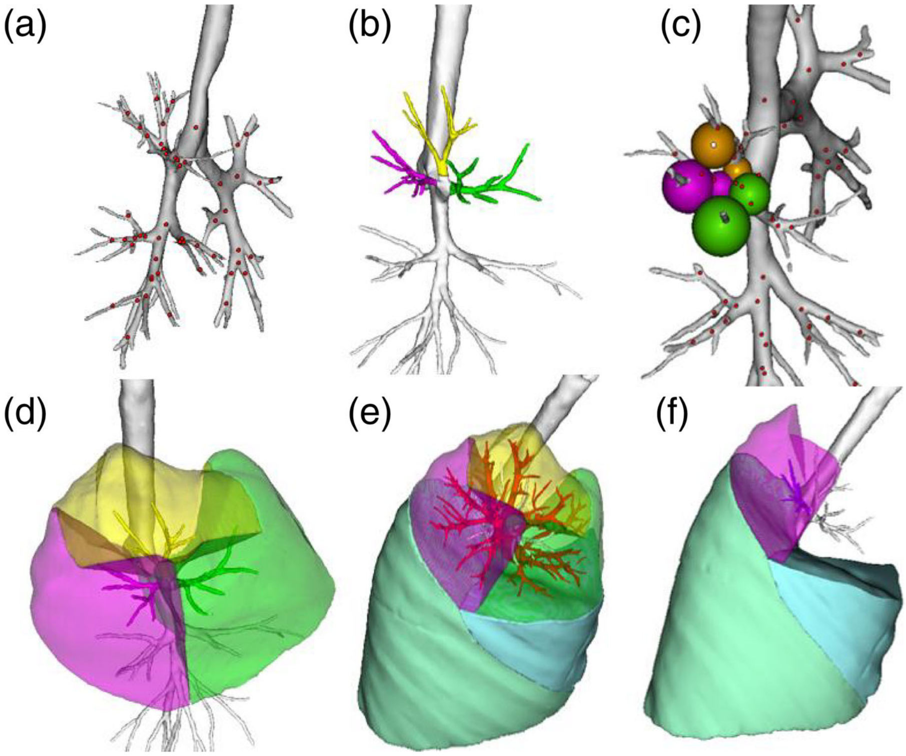

FIGURE 2 Schematic diagram of the principles of watershed analysis. (a) N points will be marked on the bronchi of each pulmonary segment or subsegment. (b) The target bronchi were set as the objects of watershed analysis. (c) The point will be the center of constant velocity external image expansion. (d) When each point meets the boundary of the lung, oblique or horizontal fissure, it will automatically stop. (e,f) As the point expands outward with equal velocity, when two points of different branches expand to coincide, they will automatically stop and naturally form an intersegmental plane

Segmentation of the right upper lobe

The premise of calculating lung segment volume is accurate segmentation. Because lung segments do not have clear interlobar clefts, segmentation is not simple and direct either in surgery or in 3D virtual images. The conventional method for producing virtual lung segments using 3D reconstruction software is to manually divide the lung lobes into segments according to the shape of the intersegmental veins.[12] The lung segment delineated by this method cannot accurately simulate the natural boundary and shape, and this would inevitably have caused a large error in the calculated volume of the lung segment and a large bias in the results of this experiment.

To obtain a more real and natural lung segment volume, we developed a watershed analysis technique to simulate the bronchial and alveolar growth processes and naturally form intersegmental planes, which has been granted the National Invention Patent of China (CN113129317B, 2022-04-08) (Figure 2(a)–(f)). The dominant-type segment (DTS) and inferior-type segment (ITS) of the right upper lobe were defined as follows. DTS: In the reconstruction model, DTS had the largest volume. Based on the volume proportion of DTS in the whole lobe, we further subdivided DTS into (1) extra-dominant segment (EDS), volume proportion >60% and (2) dominant segment (DS), volume proportion 45%–60%; and (3) subdominant segment (SDS), volume proportion >33% and <45%. ITS: This segment had the smallest volume in the lobe; it was further subdivided into (1) subinferior segment (SIS), volume proportion >25% and <33%; (2) inferior segment (IS), volume proportion 15%–25%; and (3) extra-inferior segment (EIS), volume proportion <15% (Figure 3).

Naming of the branching patterns and identifying of the segments and subsegments were performed by two thoracic surgeons, and for difficult cases, other surgeons were asked to contribute to the naming processes.

Statistical analysis

SPSS statistical software (version 24.0; IBM) was used to analyze the types of anatomical variation and their incidences in this study. For coexistence of the DTS and ITS in the right upper lobe, we used the Sankey map drawn with R software. Finally, the differences in the incidence of anatomical variation in the DTS and ITS were determined using chi-squared test, and p-values <0.05 were considered statistically significant.

RESULTS

Segmentation of the right upper lobe

Before segmentation of the right upper lobe, we first compared the differences in the volumes of the right upper lobe between men and women in this study. The mean volume of the right upper lobe in women was 643.1 ± 160.6 cm^3, and in men was 921.4 ± 243.2 cm^3; $p < 0.01$, indicating a significantly higher mean volume in males than in females.

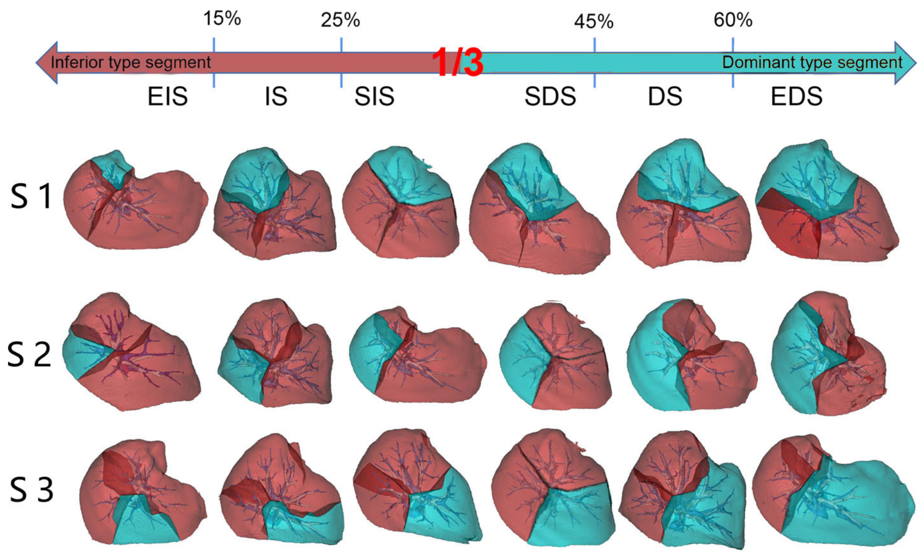

FIGURE 3 Schematic diagram of the dominant and inferior segments of RUL. DS, dominant segment; EDS, extra-dominant segment; EIS, extra-inferior segment; IS, inferior segment; S1: apical segment; S2: posterior segment; S3: anterior segment; SDS, subdominant segment; SIS, subinferior segment

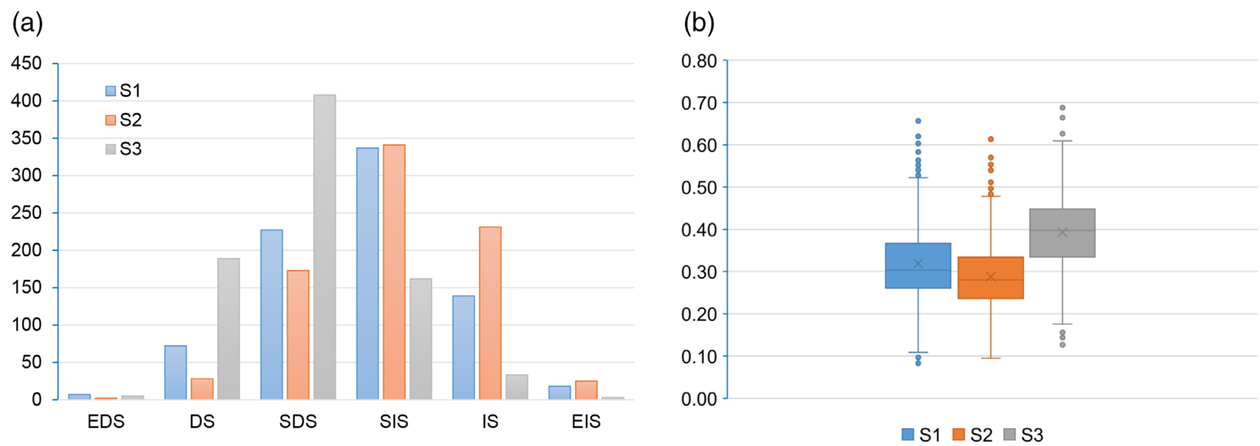

FIGURE 4 The results of segmentation of the right upper lobe. (a) The distribution of the number of dominant-type segment (DTS: EDS, DS, SDS) and inferior-type segment (ITS: EIS, IS, SIS) of the right upper lobe (S1: apical segment; S2: posterior segment; S3: anterior segment). (b) The mean volume proportion of pulmonary segment of S1, S2 and S3

The anterior segment of the right upper lobe, the DTS (DS + SDS) was dominant, accounting for 74.6% (597/800), among which the subdominant anterior segment (SDS3) accounted for the highest proportion, up to 51.0% (408/800), and the second highest proportion was that of the dominant anterior segment (DS3), accounting for 23.6% (189/800). The inferior-type segment (SIS + IS) was dominant in the posterior segment of the right upper lobe, accounting for 71.5% of cases. Among them, the subinferior posterior segment (SIS2) accounted for 42.6% (341/800), followed by the inferior posterior segment (IS2), accounting for 28.9% (231/800). The subinferior apical segment (SIS1) accounted for 42.1% (337/800) in the right upper lobe, and the second most common was the subdominant apical segment (SDS1), accounting for 28.4% (227/800) (Figure 4(a)).

The mean volume proportion of the anterior segment of the right upper lobe was 39.6 ± 8.6%, that of the posterior segment was 28.6 ± 7.9%, while that of the right upper apical segment was 31.2% ± 9.2% ($p < 0.01$ in analysis of variance test), indicating that the mean volume proportion of the anterior segment was significantly greater than that of the apical and posterior segments (Figure 4(b)).

The coexistence of SDS3 + SIS2 had the highest occurrence rate (13.1%), followed by the SDS3 + SIS1, accounting for 11.9%. The third type was the coexistence of the DS3 + IS2, accounting for 10.63% (Figure 5).

Association between the DS3 and anatomical variations (Figure 6)

Types of B3 branching and DTS3/ITS3

We compared the differences in bronchial patterns in the dominant and inferior anterior segments and found that in the DS3, the proportion of "B1 + B2, B3" type bronchi was the highest, accounting for 48.1% (91/189), followed by "B1, B2, B3" type bronchi, accounting for 39.7% (75/189). In

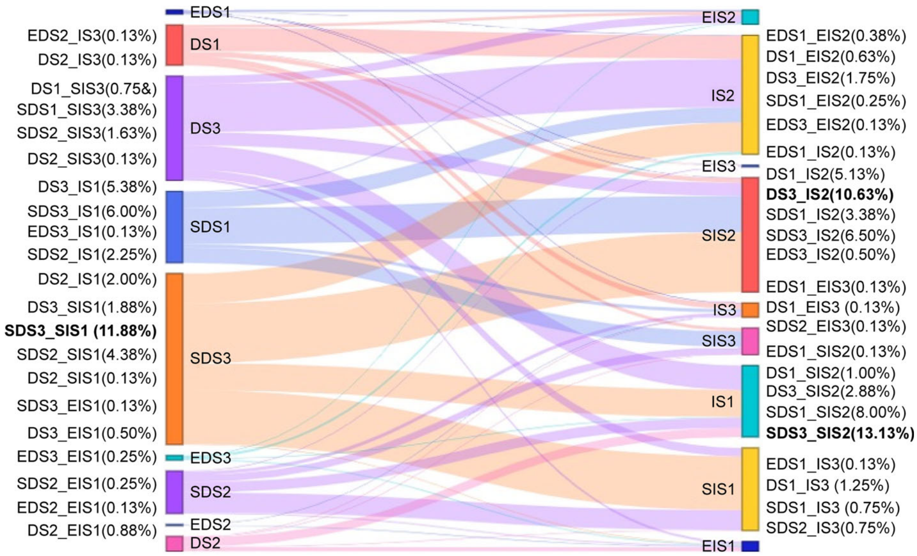

FIGURE 5 Coexistence of dominant and inferior lung segments in the right upper lobe

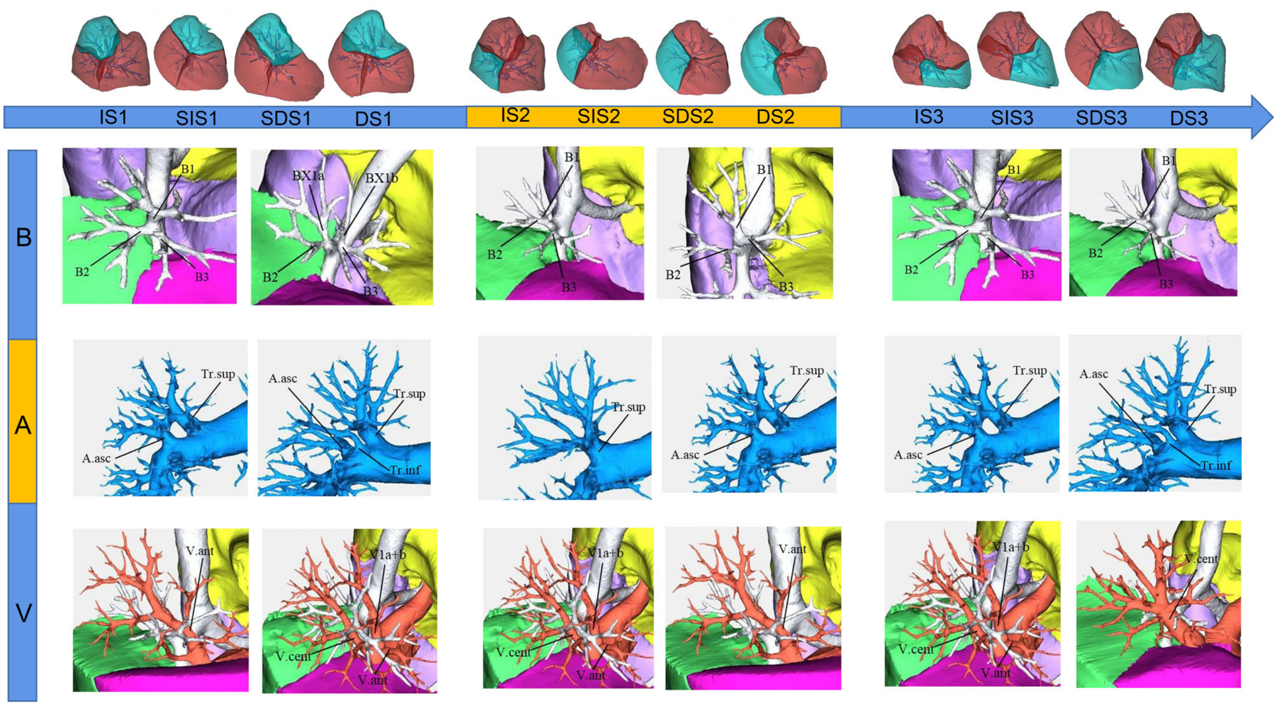

FIGURE 6 Association between anatomical variations and dominant segments

both the SDS3 and inferior anterior segment, "B1, B2, B3" type bronchi were dominant. Therefore, the DS3 and "B1 + B2, B3" are closely associated, and "B1 + B2, B3" bronchial type is dominant when the anterior segment volume proportion exceeds 45% (Figure 6).

Types of A3 branching and DTS3/ITS3

When the transformation of the right upper anterior segment is from dominant to inferior type, the incidence of trunk inferior (Tr.inf) and ascending artery (A.asc) involvement in the blood supply of the anterior segment gradually increased ($p < 0.05$, chi-squared test), indicating that Tr.inf and A.asc were more likely to participate in the anterior segment blood supply in the DS3.

Types of V3 branching and DTS3/ITS3

According to the previous description of the branching types of veins, Iab type and Ib type accounted for 46.5% (372/800) and 29.4% (235/800), respectively. Therefore, we identified the relatively rare anterior vein type (AVT) and central vein type (CVT) as variation types and further analyzed the differences in their incidences in the dominant and inferior anterior segments. AVT accounted for 3.7% in DS3, 3.5% in SDS3, 3.1% in SIS3, and 3.0% in IS3 ($p = 0.990$, chi-squared test), indicating that there was no statistically significant difference in the occurrence rate of AVT in the dominant and inferior anterior segments. CVT accounted for 10.5% in DS3, 9.4% in SDS3, 6.8% in SIS3, and 6.1% in IS3 ($p = 0.596$, chi-squared test). Due to the limited study sample size and small occurrence rate of CVT, the statistical difference was not significant. However, we still found a tendency for CVT to be concentrated in the DS3.

Therefore, with the volume of the anterior segment of the right upper lobe increasing, the occurrence rate of the bifurcated type of bronchus (B1 + 2, B3), the "central vein type" (CVT) and the involvement of the Tr.inf and A.asc in the blood supply of anterior segment gradually increased.

Association between DS1 and anatomical variations (Figure 6)

Types of B1 branching and DTS1/ITS1

In the DS1, "B2 + BX1a, BX1b + B3" type bronchi accounted for the highest proportion, up to 29.17% (21/72). "B2 + BX1a, BX1b + B3" type bronchus was the second commonest in SDS1, accounting for 17.18% (39/227). "B2 + BX1a, BX1b + B3" type bronchus was relatively uncommon in the inferior type apical segment (SIS1 + IS1), of which its incidence rates in SIS1 and IS1 were 3.5% (12/337) and 10.8% (15/139), respectively. Therefore, the incidence of B1-deficient bronchi in DTS1 was much higher than that in the ITS1 ($p < 0.001$ in chi-squared test) (Figure 6).

Types of A1 branching and DTS1/ITS1

Most of the apical arteries are type I, that is, A1a and A1b are from trunk superior (Tr.sup), and variation occurs only in a few cases. Therefore, association analysis of anatomical variation of the apical arteries and SDS and SIS was not performed.

Types of V1 branching and DTS1/ITS1

As for the association between venous variations and the transformation of DTS1/ITS1, we also focused on the AVT and CVT which have relatively low occurrence rates, and further analyzed the differences in their incidence in DTS1 and ITS1. AVT accounted for 4.2% in DS1, 0.4% in SDS1, 3.9% in SIS1, and 7.2% in IS1. There was a statistically significant difference in the occurrence rate of AVT in the transformation of DTS1/ITS1 ($p = 0.002 < 0.05$, chi-squared test); that is, AVT was more closely related to IS1. CVT accounted for 4.2% in DS1, 6.6% in SDS1, 11.1% in SIS1, and 8.6% in IS1. There was no statistically significant difference in the occurrence rate of CVT in SDS and SIS ($p = 0.164 > 0.05$, chi-squared test).

Given the above analysis, with the volume of the apical segment of the right upper lobe increasing, the occurrence rate of the B1-deficient bronchi type (B2 + BX1a, BX1b + B3) increased and the occurrence rate of the anterior vein type (AVT) decreased.

Association between DS2 and anatomical variations (Figure 6)

Types of B2 branching and DTS2/ITS2

In the inferior posterior segment (IS2), the "B1+ B2, B3" type bronchus accounted for 36.8% (85/231), followed by "B1, B2, B3" type bronchus, accounting for 35.9% (83/231). The dominant posterior segment (DS2 + SDS2) and the subinferior posterior segment (SIS2) had the highest proportion of "B1, B2, B3" type bronchus, and the proportions of "B1 + B2, B3" in the three types were 0%, 18.4%, and 22.9%, respectively, ($p < 0.01$, chi-squared test); therefore, IS2 is closely related to the "B1 + B2, B3" bronchus; that is, when the proportion of the volume of the posterior segment is <25%, the bronchial type is usually "B1 + B2, B3" (Figure 6).

Types of A2 branching and DTS2/ITS2

With the continuous enlargement of the posterior segment, the proportion of recurrent artery (A.rec) participating in its blood supply gradually increased. This difference was statistically significant ($p < 0.05$, chi-squared test). The proportion of superior artery (A.sup) participating in the posterior segment blood supply also gradually increased ($p = 0.122$, chi-squared test). Due to the limited sample size and the small occurrence rate of A.sup, the difference was not statistically significant. However, we still found a tendency of A. sup to concentrate on the dominant posterior segment.

Types of V2 branching and DTS2/ITS2

As for the relationship between venous variation and the dominant and inferior posterior segments, we also focused on the AVT and CVT with relatively low occurrence rates, and further analyzed the differences in their incidence rates in the dominant and inferior posterior segments. AVT accounted for 14.8% in DS2, 6.3% in SDS2, 2.6% in SIS2, and 1.7% in IS2 ($p < 0.05$, chi-squared test), indicating a statistically significant difference in the occurrence rate of AVT in the dominant and inferior posterior segments; that is, AVT was more closely related to the dominant posterior segment. CVT accounted for 14.8% in DS2, 8.6% in SD2, 9.4% in SIS2, and 8.2% in IS2 ($p = 0.644$, chi-squared test), indicating no statistically significant difference in the occurrence rate of CVT in the dominant and inferior posterior segments.

Combining the above analysis, we found that with the volume of the posterior segment of the right upper lobe increasing, the occurrence rate of the recurrent artery (A.rec) participating in the blood supply of posterior segment and the anterior vein type (AVT) gradually increased.

DISCUSSION

The pulmonary segment is an anatomical unit, which is relatively independent in structure and function.[2] We have previously lacked the effective tools to accurately measure the shape and volume of lung segments; however, today with the help of high-precision three-dimensional reconstruction technology, we can accurately divide and measure the volume of lung segments, define the dominant and inferior lung segments, and enrich the concept of lung segments in anatomy.

The distribution of dominant and inferior lung segments has a certain stability: in the right upper lobe, the DTS is concentrated in the anterior segment, while the ITS is distributed relatively equally in the apical/posterior segment. For pulmonary nodules in the dominant pulmonary segments, subsegmentectomy can be considered under the principle of sufficient margin, to preserve as much lung function as possible; when nodules are located in the inferior segment of the lung, single segmentectomy is often unable to guarantee sufficient resection margins, and combined segmentectomy or expanded single segmentectomy is needed. The introduction of the perspective of superior and inferior lung segments will enrich the methods and connotation of minimally invasive resection and improve the accuracy and effectiveness of sublobectomy.

During segmentectomy, sufficient exposure and suture of pulmonary segmental arteries, veins, and bronchi are the prerequisites for successful resection of the target pulmonary segment.[13] However, anatomical variations pose several challenges in pulmonary segmentectomy.[6] Therefore, this study explored and summarized the regularity of anatomical variation in the context of dominant and inferior lung segments. We found that the dominant and inferior lung segments and anatomical variations are complementary to each other.

Different dominant segments have different characteristics of anatomical variation, so they have different operative risks. The dominant anterior type has the high occurrence rate of the "central vein type" (CVT), the trunk inferior (Tr.inf) and ascending artery (A.asc) in the blood supply of the anterior segment, which will bring difficulties and challenges for the sufficient exposure and suture of pulmonary segmental arteries, veins, and bronchi during anterior segmentectomy. The dominant apical type has a high occurrence rate of the B1-deficient bronchi type (B2 + BX1a, BX1b + B3), which could cause problems for the sufficient exposure and suture of apical segmental structures during apical segmentectomy. The dominant posterior type has a high occurrence rate of the recurrent artery (A.rec) participating in the blood supply of posterior segment, which will increase the difficulty and risk of posterior segmentectomy. Therefore, the findings of dominant types of right upper lobe can be used to guide preoperative planning, minimize surgical risks, and improve the safety of minimally invasive pulmonary surgery.

The use of image data to reconstruct blood vessels, bronchies, and subnodules in the lungs has been proven to be invaluable. Three-dimensional reconstruction of the pulmonary trachea and vascular reconstruction in the sublung leaf removal scheme is outstanding. Although it is not technically difficult to achieve, it is expensive and, at present, has not been fully replaced by puncture positioning technology. Patients should receive appropriate guidance in order to comprehensively consider the benefits and risks of treatment.

AUTHOR CONTRIBUTION

Contributions NQ conceived and designed the study. WZ performed administrative support. ZH, XP drafted the manuscript, JT, FR performed provision of study materials. KJ, JH performed data collection an assembly. BY performed Data analysis and interpretation. All authors have read and approved the final manuscript.

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CONFLICT OF INTEREST

All authors declare no conflict of interest.

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