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Application of three-dimensional reconstruction of left upper lung lobes in anatomical segmental resection

Kun Fan | Jinteng Feng | Yixing Li | Bohao Liu | Runyi Tao | Zhiyu Wang | Heng Zhao | Yanpeng Zhang | Jiansheng Wang | Guangjian Zhang

Department of Thoracic Surgery, The First Affiliated Hospital of Xi'an Jiaotong University, Xi'an, China

Correspondence
Guangjian Zhang, Department of Thoracic Surgery, The First Affiliated Hospital of Xi'an Jiaotong University, 277# Yanta West Road, Xi'an, Shaanxi 710061, China.
Email: michael8039@mail.xjtu.edu.cn

Abstract

Background: The lobar and segmental anatomy are the basis for anatomical pulmonary segmentectomy.

Methods: From October 2017 to June 2021, 136 patients with small pulmonary nodules scheduled for anatomical pulmonary segmentectomy at our institution underwent three-dimensional (3D) lung reconstruction. The anatomy of the left upper lobe (LUL) was statistically analyzed and graphically mapped using the reconstructed models, and the role of this reconstruction method in performing pulmonary segmentectomy was explored.

Results: Through the analysis of the reconstructed models, the upper stem (S1 + 2 + 3) bronchus was classified as having two (94/136 cases) or three branches (42/136 cases). The upper stem artery had two branches in 24/136 patients, three in 60/136 cases, four in 44/136 cases, and five in 8/136 cases. A total of 103/136 upper stem veins had two branches, 26/136 had three branches, and 7/136 had four branches. The lingual stem (S4 + 5) bronchus was two-branched in 116/136 cases and three-branched in 20/136 cases, while the lingual artery was single-branched in 61/136 cases, two-branched in 70/136 cases, and three-branched in rare cases (5/136 cases). The lingual stem vein was unbranched in 119/136 cases and two-branched in 17/136 cases. Additionally, six unusual variants (<5%) were identified: one in the bronchus, with four cases; three in the pulmonary artery, with six cases; and two in the pulmonary vein, with two cases.

Conclusions: 3D reconstruction can yield results similar to specimens for lung segment studies. The reconstruction strategy and the data presented in this article will be valuable references for thoracic surgeons performing anatomic resections.

KEYWORDS
left upper lung, lung segmental anatomy, three-dimensional reconstruction

INTRODUCTION

With the popularity of computed tomography (CT) and increased awareness of health care among the population, the early-stage lung cancer detection rate has greatly increased compared to the past,[1] making anatomical segmental lung resection a common procedure in thoracic surgery. Due to the extremely fine anatomical requirements of segmental resection, intraoperative tracheal and vascular dissection must be precise down to the segmental or even subsegmental level, which includes a complex structure and numerous variants, making segmentectomy a significant challenge for thoracic surgeons.[2]

Therefore, a careful and accurate preoperative assessment of the patient's anatomy becomes important to ensure a smooth operation. The most accurate and intuitive method of assessing the anatomy of lung segments in the past has undoubtedly been anatomical specimens, but this method does not apply to the preoperative evaluation of patients. As a result of the development of 3D reconstruction techniques in recent years, the scalpel has largely been phased out of the toolkits of anatomists, allowing us to study the morphology and structure of human tissues and organs in three dimensions and in real-time, even without the use of anatomical specimens.[3–5]

This study used Materialise's interactive medical image control system (MIMICS 20.0) to perform preoperative 3D reconstruction routinely on 136 patients with small pulmonary nodules scheduled for segmental lung resection at our center. We then collected and organized these reconstructed data, applied them to an anatomical study of LULs, and summarized the value of this reconstruction method as an aid to lung segment resection.

METHODS

Data acquisition

Since October 2017, patients in our department with small pulmonary nodules have been screened using inclusion and exclusion criteria, and preoperative chest-enhanced CT has been conducted routinely. A 256-row spiral CT, PHILIPS Brilliance iCT was used for scanning. The contrast agent was iohexol at a concentration of 300 mg/ml and a rate of infusion of 3 ml/s, and finally, a CT image with a layer thickness of 1 mm was obtained. Mimics 20.0 software was used to perform the subsequent 3D reconstruction. By June 2021, a total of 136 reconstructions had been completed, and the reconstruction data had been retained for anatomical structural statistics and analysis. All reconstructions were done by the same clinician and reviewed by two supervising physicians.

Inclusion criteria

(1) Nodules were isolated peripheral nodules, ≤2 cm in diameter, and met one of the following: (a) Pathology was adenocarcinoma in situ of the lung, (b) nodule ground-glass component ≥50% on CT, and (c) nodule multiplication time ≥400 days, (2) Planned lung segment cut edge ≥2 cm from the tumor or ≥ tumor diameter. (3) CT showed no hilar and mediastinal lymph node metastasis. (4) Major organ functions such as heart, lung, liver, and kidney can tolerate the surgery. (5) Age: 18–75 years old.

Exclusion criteria

(1) Distant organ metastases, (2) those who had undergone lung surgery or radiotherapy, (3) female patients in pregnancy or lactation, (4) those without informed consent due to psychological, family, and social factors, (5) patients with a history of other malignancies within 5 years prior to admission, except nonmelanoma skin cancer, in situ cervical cancer, or cured early prostate cancer, and (6) other patients who are not controllable inoperable.

Rejection criteria

(1) Intraoperative open chest due to the need for transit, (2) extensive pleural adhesions, and (3) tumor pleural metastases (including malignant pleural fluid).

Judgement of branching pattern and variation

The determination of the bifurcation and co-stem of the tree structure remains ambiguous, owing to a lack of clarity in earlier investigations. In this study, the bifurcation and co-stem were still determined by the location of bronchial and vascular emanations at each level, and it was clearly stated that co-stem length within 3 mm is judged as just a tendency to co-stem, actually recorded as bifurcation. A common stem of 3 mm or greater is genuinely considered a co-stem (Figure 1). In addition, this study defines the branching patterns with less than 5% frequency as rare variants (Table1).

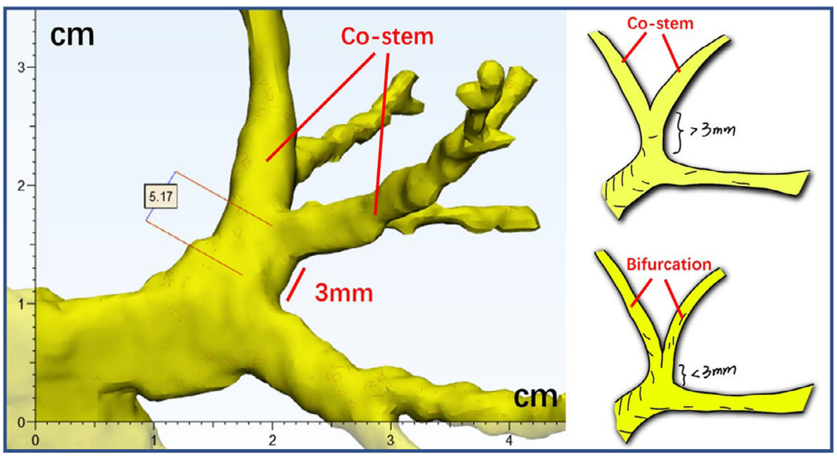


FIGURE 1 The determination of the bifurcation and co-stem in this study. Within 3 mm, co-stem length is considered as only a tendency to co-stem, which is really recorded as bifurcation. A co-stem is defined as a shared stem with a diameter of 3 mm or more

TABLE 1 Branching pattern of left upper lobe

	Branching pattern	Case	Proportion
Bronchus			
Upper stem	Two-branch	94	69.12%
	Three-branch	42	30.88%
Lingual stem	Two-branch (vertical)	101	74.26%
	Two-branch (horizontal)	14	10.29%
	Three-branch	21	15.44%
Artery			
Upper stem	Two-branch	24	17.65%
	Three-branch	60	44.12%
	Four-branch	44	32.35%
	Five-branch	8	5.88%
Lingual stem	Single-branch	61	44.85%
	Two-branch	70	51.47%
	Three-branch	5	3.68%
Vein			
Upper stem	Two-branch	103	75.74%
	Three-branch	26	19.12%
	Four-branch	7	5.15%
Lingual stem	Single-branch	119	87.5%
	Two-branch	17	12.5%
Reflux position of lingual stem	Left superior pulmonary vein (LSPV)	116	85.30%
	Left atrium	20	14.71%
	Left inferior pulmonary vein (LIPV)	1	0.74%

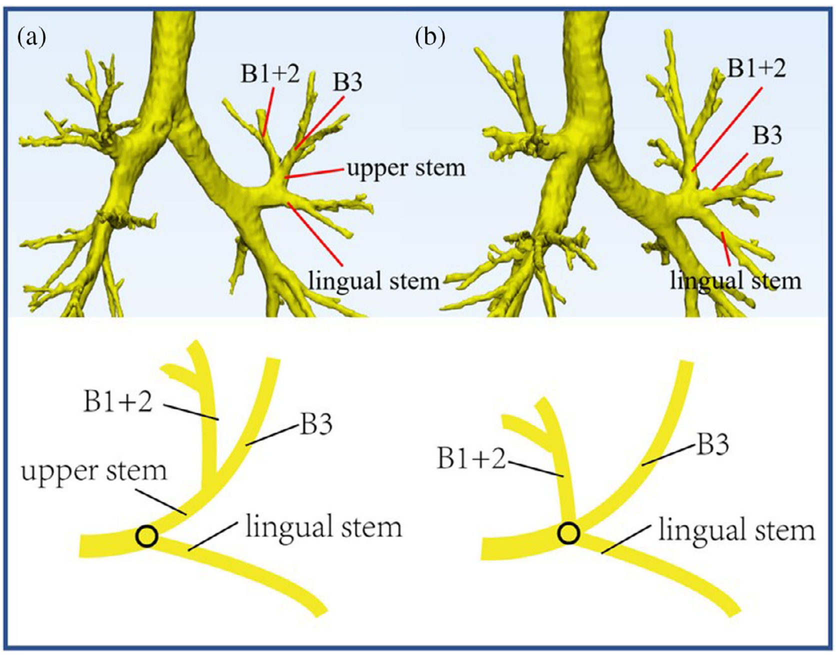


FIGURE 2 The upper and lingual stems of LUL. (a) Two-stem pattern and (b) three-stem pattern. B12, apicoposterior segmental bronchus. B3, anterior segmental bronchus

RESULTS

General information

A total of 136 patients with small pulmonary nodules were included; 76 males and 60 females, aged 37–75 (56.89 ± 8.81) years. The lesion diameters were 4.9–19.7 (11.97 ± 4.03) mm. Seventy cases had isolated lesions in the right lung, and 54 cases had isolated lesions in different lungs. Multiple lesions were seen in 14 cases, including six cases where multiple lesions were present in distinct lungs and eight cases where multiple lesions were present in the same lung.

Bronchus branching pattern

In 131 cases (96.32%), the bronchi in the upper lobe of the left lung could be divided into two stems, namely the upper and the lingual stem (Figure 2(a)). Five patients (3.68%) had a three-stem pattern, all due to a low level of bifurcation of the upper stem, with the intrinsic and anterior segments of the bronchi emanating from the same point as the lingual stem (Figure 2(b)).

The upper stem bronchi are generally divided into two-branch, and three-branch types, with the two-branch type

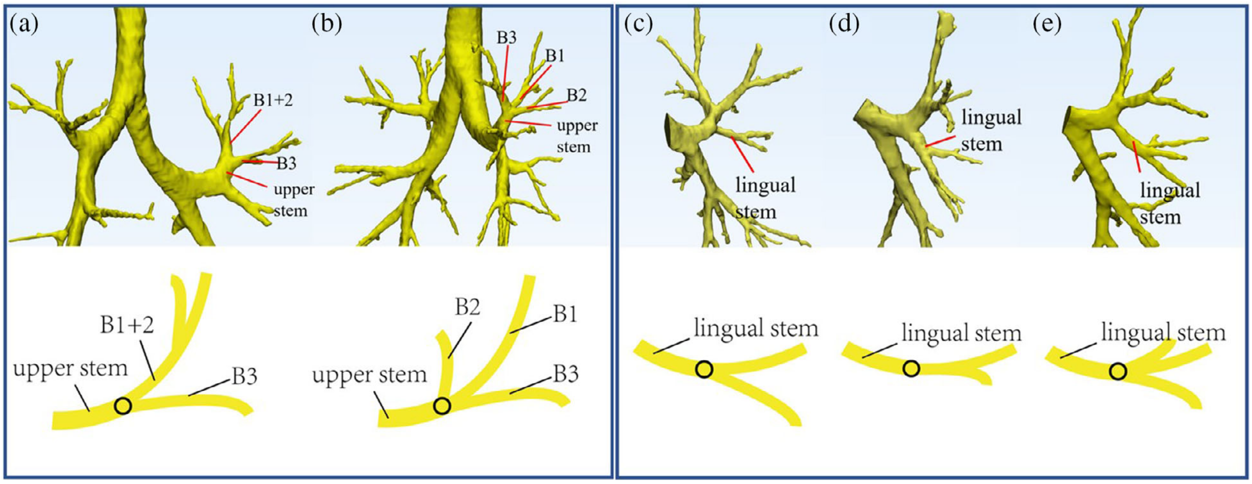


FIGURE 3 Bronchus branching pattern of LUL. Upper stem: (a) Two-branch and (b) three-branch. Lingual stem: (c) Two-branch (vertical), (d) two-branch (horizontal), and (e) three-branch. B1, apical segmental bronchus. B2, posterior segmental bronchus. B1 + 2, apicoposterior segmental bronchus. B3, anterior segmental bronchus

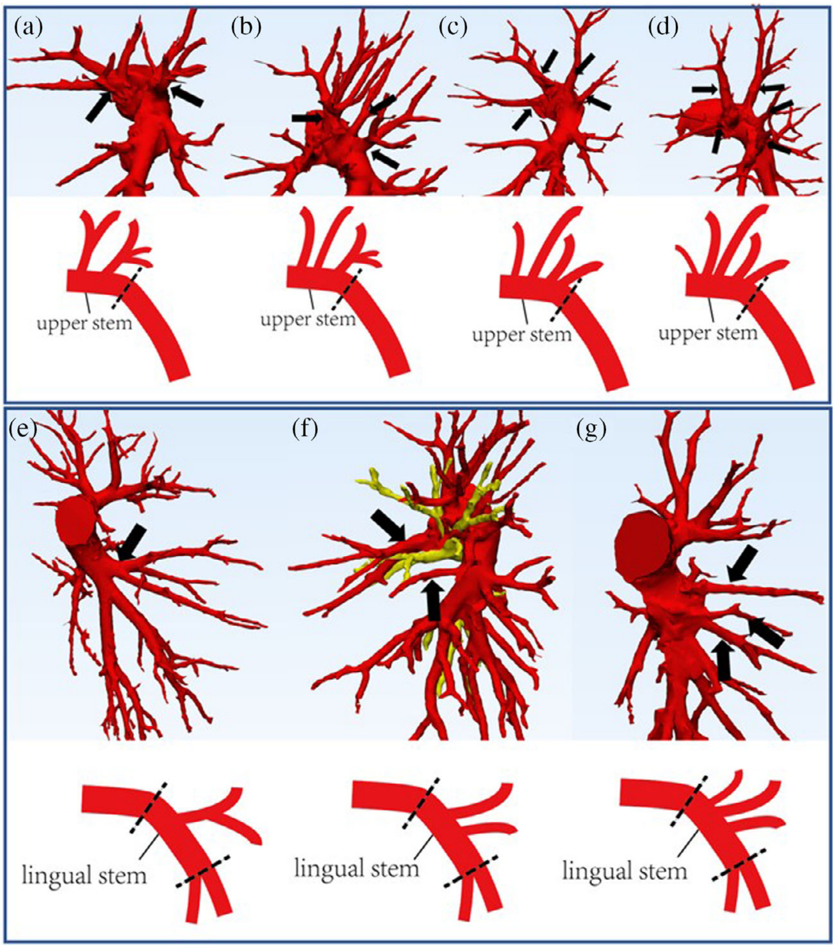


FIGURE 4 Artery branching pattern of LUL. Upper stem: (a) Two-branch, (b) three-branch, (c) three-branch, and (d) five-branch. Lingual stem: (a) Two-branch, (b) three-branch, (c) three-branch, and (d) five-branch

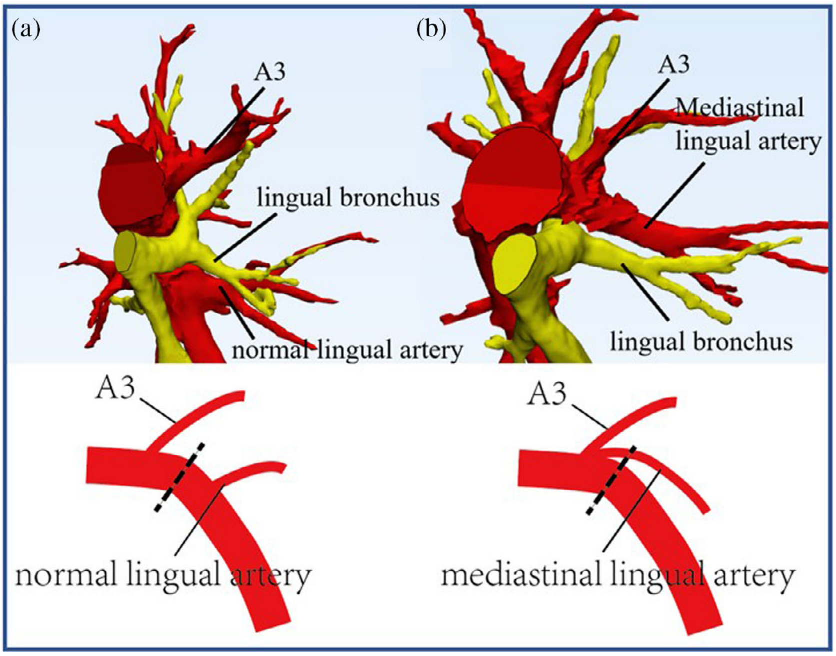


FIGURE 5 (a) Normal lingual artery and (b) mediastinal lingual artery. A3, anterior segmental artery

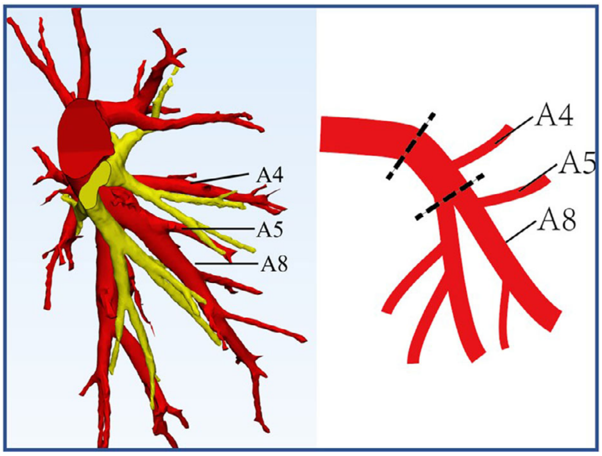


FIGURE 6 One case showed the inferior lingual segmental artery originating from the anterior basilar artery. A4, superior lingual segmental artery. A5, inferior lingual segmental artery. A8, anterior basilar artery

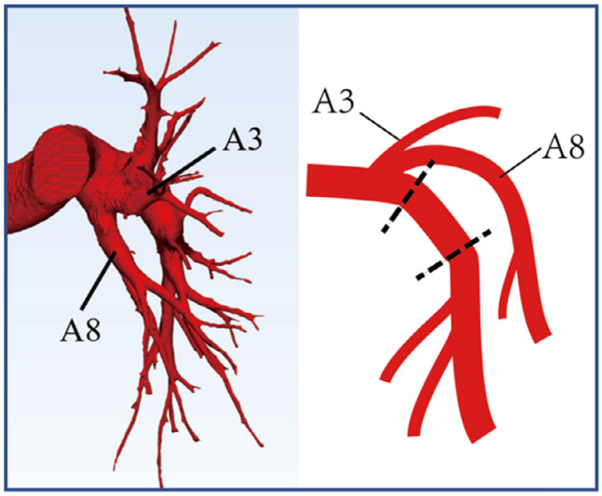


FIGURE 7 One case showed the anterior basilar artery emanated from the root of the left pulmonary artery and co-stemed with the anterior segmental artery. A8, anterior basilar artery. A3, anterior segmental artery

being the most common (94/136 cases) (Figure 3(a)), and three-branch cases can often be seen (42/136 cases) (Figure 3(b)). The two-branch type is mostly apical-post co-stem (B1 + 2, B3), and occasionally apical-anterior co-stem (B1 + 3, B2) can be seen. The lingual stem bronchi were predominantly two-branch (115/136 cases), and the direction of passage was frequently vertical (101/136 cases) (Figure 3(c)) but also horizontal (14/136 cases) (Figure 3(d)). Additionally, a three-branch pattern was seen (21/136 occurrences) (Figure 3(e)).

Artery branching pattern

We counted the branches emerging from the upper stem and found between two and five branches. Three branches (60/136 cases) (Figure 4(a)) and four branches (44/136 cases) (Figure 4 (b)) were the most frequently encountered, followed by two branches (24/136 cases) (Figure 4(c)) and five branches (8/136 cases) (Figure 4(d)).

The pulmonary artery begins to descend when it crosses the bronchus, and the majority of the lingual segment's arteries originate here, generally one (61/136 cases) (Figure 4(e)), or two (70/136 cases) (Figure 4(f)), or in a few cases three (5/136 cases) (Figure 4(g)). Suppose the lingual artery (A4 +5) originates at the emanation of the anterior segmental artery (A3) and travels down from the front of the bronchus, it is referred to as a mediastinal lingual artery (Figure 5(b)) and observed in 26 cases (19.12%) in our study. Additionally,

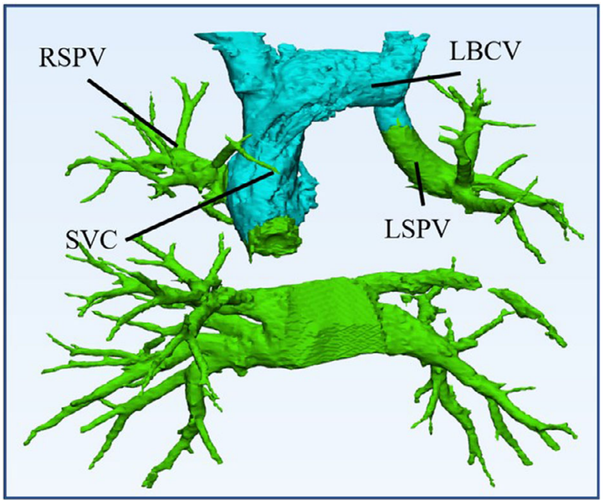


FIGURE 8 Both superior pulmonary veins return to the right heart system. LSPV, left superior pulmonary vein. RSPV, right superior pulmonary vein. LBCV, the left brachiocephalic vein. SVC, superior vena cava

an uncommon variant of the inferior lingual segmental artery (A5) was observed in one case (0.74%) that originated from the anterior basilar artery (A8) (Figure 6), and in another case (0.74%), A8 emanated from the root of the left pulmonary artery and co-stemmed with A3 (Figure 7).

Vein branching pattern

Typically, the left superior pulmonary vein (LSPV) returns to the left atrium. However, in this study, there was one variant - the LSPV returned to the left brachiocephalic vein (LBCV), accompanied by the right superior pulmonary vein (RSPV) returning to the superior vena cava (SVC) (Figure 8).

The posterior segment of the left upper lung vein (V2) is thick and typically joins the apical segment (V1) to form a thick arch. The anterior section (V3) is thinner and has a variable branch count. According to the number of branches returning to the LUL pulmonary veins, the following categories were found: (1) two branches (103/136 cases): typically,

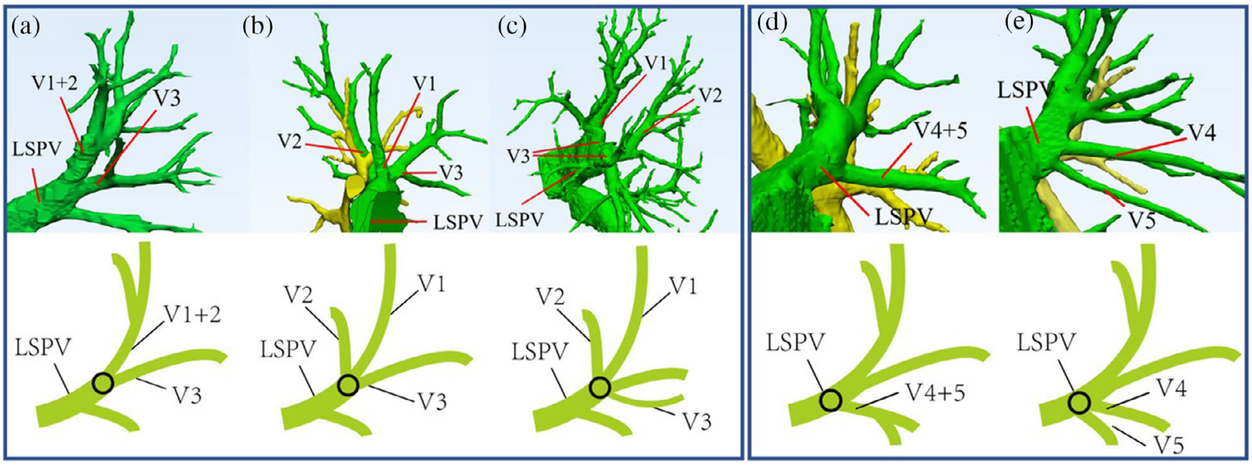
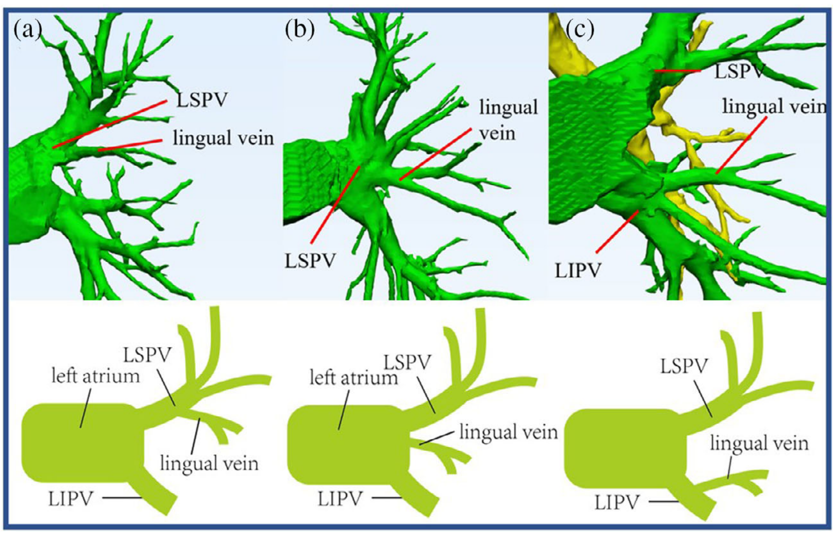


FIGURE 9 Vein branching pattern of LUL. Upper stem: (a) Two-branch, (b) three-branch and (c) four-branch. Lingual stem: (d) Single-branch, and (e) two-branch. LSPV, left superior pulmonary vein. LSPV, left superior pulmonary vein. V1, apical segment vein. V2, posterior segment vein. V1 + 2, apicoposterior segment vein. V3, anterior segment vein. V4, superior lingual segmental vein. V5, inferior lingual segmental vein

FIGURE 10 Reflux position of lingual stem vein. (a) Reflux to the LUL pulmonary vein, (b) direct reflux to the atrium, and (c) reflux to the left lower lobe pulmonary vein. LSPV, left superior pulmonary vein



the apical and posterior segments (V1) converge to create the apicoposterior segment vein (V1 + 2), whereas the anterior segment vein (V3) returns alone (Figure 9(a)), (2) three branches (26/136 cases): the apical and posterior segments of the vein form a common trunk, and the subsegment of the anterior segment eventually splits into two fine branches of the vein (Figure 9(b)), and (3) four branches (7/136 cases): usually generated by the anterior vein divided into two tiny reflux branches (Figure 9(c)).

The lingual veins converged into single reflux in the majority of cases (119/136) (Figure 9(d)) and separated into two refluxes in a few cases (17/136) (Figure 9(e)). According to the location of its reflux, there were three types of cases: (1) reflux to the LSPV (116/136 cases) (Figure 10(a)), (2) direct reflux to the left atrium (20/136 cases) (Figure 10(b)), and (3) reflux to the left inferior pulmonary vein (LIPV) (1/136 cases) (Figure 10(c)).

DISCUSSION

With the evolution of minimally invasive surgery and the notion of precision medicine, lung cancer surgery is becoming more refined and personalized, placing higher demands on studying lung segment anatomy. The British Thoracic Society established the international nomenclature for lung segments in 1950, which has remained in use until today.[6] However, this nomenclature alone cannot accurately assess each patient's lung anatomy in clinical practice because it only describes the population's most common and representative branching pattern without mentioning other types and variants. Thus, it cannot accurately guide the performance of lung segment resection.

Many early cadaveric studies[7,8] and recent clinical case reports[9–12] have examined the anatomical variations of lung segments, confirming the highly complex and variable characteristics of lung segments. This complexity greatly increases the risk of intraoperative vascular injury during lung segment resection. The high blood flow and velocity in the pulmonary circulation adjacent to the heart are often hazardous in intraoperative bleeding, which requires thoracic surgeons to have a more precise knowledge of each individual's anatomy prior to surgery. As a result, it is critical to conduct anatomical morphological examinations of the bronchi and pulmonary arteries to perform anatomical lung segmental resection safely and precisely.

Three-dimensional reconstruction technology is an excellent fit for this requirement. With regard to the Mimics 20.0 software that was used in this study: (1) The software is not platform-dependent and can be installed on a portable laptop. (2) Clinicians can also use it because the software does not require advanced computer imaging expertise. (3) The resulting graphics are of great quality, and the reconstructed images based on thin CT with a layer thickness of 1 mm closely resemble anatomical specimens. (4) Reconstructed graphics can be output in common 3D file formats so that they can be communicated between different devices. It enables clinicians to conduct immediate three-dimensional and visual observation even while performing surgery. Preoperative 3D reconstruction can also assist the operator in identifying the nodule's position early, defining the scope of surgical resection, determining the surgical approach, and determining the amount of tissue to be removed. The introduction of this approach will flatten the learning curve for segmental lung surgery, making it more accessible to beginner surgeons and eventually reaching universal access to segmental lung resection.

In the current study, for example, 3D reconstruction helped us rapidly discover various branching patterns and unusual variants in the LUL prior to surgery, and the results were comparable to those previously obtained utilizing anatomical specimens. Our department counted and examined the structural patterns and uncommon variants of the LUL of the lung using 3D reconstructed images of 136 individuals with small pulmonary nodules in this study. By and large, the first and second level structures are generally stable and hence unable to form distinct branching patterns; yet, the fourth level structure is too changeable and disordered and thus incapable of forming a fixed pattern as well. The anatomy at the tertiary level (lung segment level), on the other hand, is more variable but with some regularity, and as the main target of lung segment surgery, it is the object of focus in this article.

We defined rare variants as those having a frequency of occurrence of 5% or less, and we counted six uncommon variants, totaling 12 cases. Although rare variants are relatively uncommon in the population, once they appear in the surgical region, operators often make empirical judgments that lead to mishandling or even errors and, therefore, should be given sufficient attention. The higher the level of variation, the greater the impact on the surgical operation. Notably, most of the lingual segmental arteries start in the descending part and are positioned inferiorly. However, a unique scenario frequently occurs in the lung segment of the LUL. The lingual segmental artery originates from the first branch of the LUL and travels in front of the upper lobe bronchi, where it is referred to as the mediastinal lingual segmental artery. It is easily misinterpreted if not identified during the intrinsic or anterior segment resection. There were 26 cases (19.12%) of the mediastinal lingual segmental artery in this study, which is a significant number, and operators should pay special attention to them.

Although the statistical results for each anatomical subtype in this investigation varied from earlier studies, the overall trend remained consistent. Given that earlier results were likewise inconsistent, we believe that this disagreement is more likely attributable to the still very small sample size or discrepancies in previous branching procedures than to anatomical peculiarities of the early NSCLC population.

There are still limitations in this study. First, individual fine intraoperative branches (typically 1 mm) were not properly reflected on the reconstruction, which may affect the results of branching patterns and variant types. Furthermore, this study did not compile precise statistics on subsegmental branching, owing to the complex structure of subsegmental levels and the huge volume of data, which will be presented sequentially.

In conclusion, this study discusses the branching pattern and anatomical variations of the LUL of the lung in 136 patients through 3D reconstruction. The findings indicate that the anatomical structure of the lung segments in the LUL is complex, with multiple variants and substantial individual variations. The results illustrate that 3D reconstruction can assist the operator in making an adequate individualized assessment of the patient's anatomy. The data in this study also have some reference value for the development of anatomic lung segment resection in the LUL of the lung.

CONFLICT OF INTEREST

The authors declare that there are no competing interests.

ORCID

Kun Fan https://orcid.org/0000-0002-2634-5774
Yixing Li https://orcid.org/0000-0002-1520-1222

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