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Anatomy of the lung revisited by 3D-CT imaging

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Abstract

The anatomy of the lung was originally described based on data acquired from cadaveric studies and surgical findings. Over time, computed tomography (CT) and three-dimensional (3D) imaging techniques have been developed, allowing for reconstruction and understanding of lung anatomy in a more intuitive way. The wide adoption of 3D-CT imaging technology has led to a variety of anatomical studies performed not only by anatomists but also by surgeons and radiologists. Such studies have led to new or modified classification systems, shed light on lung anatomy from

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a useful surgical viewpoint, and enabled us to analyze lung anatomy with a focus on particular anatomical features. 3D images also allow for enhanced pre- and intra-operative simulation, improved surgical safety, enhanced educational utility, and the capacity to perform large-scale anatomical studies in shorter time frames. We will review here the key features of 3D-CT imaging of the lung, along with representative anatomical studies regarding (I) general lung anatomy, (II) anatomy of the right and left lobes, and (III) features of interlobar vessels. The current surge of 3D imaging analysis shows that the field is growing, with the technology continuing to improve. Future studies using these new and innovative methodologies will continue to refine our understanding of lung anatomy while enhancing our ability to perform safe and effective surgical resections.

Keywords

Lung; anatomy; 3D imaging

Introduction

The anatomy of the lung has been studied in detail since the 1930's with an international nomenclature proposed in 1950 (1). Knowledge of lung segments has been periodically revised, mostly based on input from cadaveric studies and surgical findings (2–5). This led to a textbook presented by Yamashita in 1978 which today remains widely used and a key reference in many publications (5). However, information collected from cadavers has drawbacks including postmortem modifications or limitations in analysis due to difficulties procuring cases. Since these initial cadaveric and surgical studies, non-invasive imaging technology has flourished enabling analyses from a radiological perspective. In particular, computed tomography (CT) and three-dimensional (3D) imaging has made it possible to reconstruct the anatomy of the lung allowing for a more intuitive understanding of the spatial relationships between structures (6). 3D-CT imaging involves postprocessing of the entire multidetector CT data set to generate 3D volume-rendered images, allowing for visualization and manipulation of objects represented as sample data in 3D. The adoption of 3D-CT imaging has led to a variety of analyses led not only by anatomists but also by surgeons and radiologists. Thoracic surgeons also became actively engaged in anatomical analysis using 3D imaging, partly driven by the surgical need to better understand the anatomy of the lung (7–12). We will review here key features of 3D-CT imaging of the lung and present representative anatomical studies based on 3D-CT images.

Features of 3D-CT Imaging

A major advantage of 3D-CT imaging lies in its ability to allow for better recognition of anatomical structures compared to two-dimensional (2D) images (Table 1). Although conventional CT images do include information necessary to analyze anatomy, they are not always sufficient to fully perceive the spatial relationships between anatomical structures. A trained physician could recreate anatomical structures in his or her mind (13), but the technique requires skill and is time consuming. 3D-CT images enable surgeons to quickly and more intuitively recognize the anatomy and associated anomalies (14). Also, images can be shared for educational purposes or used for pre- and intra-operative simulation (10).

Another benefit of 3D-CT imaging is the associated improvement in surgical safety. With the increasing number of segmentectomies being performed, a detailed understanding of each patient's unique anatomy, which includes the spatial relationship between bronchial, vascular, and parenchymal structures, is of increasing importance. In 2011, Oizumi *et al.* presented the usefulness of preoperative 3D-CT imaging in thoracoscopic segmentectomy and reported a 98% success rate (8). Many others have also reported the benefits of 3D-CT imaging in lung surgery (15). Surgeons performing segmentectomy are also more likely to be faced with segmental variations, and some commonly encountered variations have been analyzed in more detail, such as the subsuperior segment (16–18). Accordingly, an understanding of segmental anatomy and associated anatomic variants is essential for segmentectomy (Figure 1). However, a basic knowledge of anatomical variations is also beneficial when performing a routine lobectomy. We should always bear in mind the possibility of encountering common variations, such as an anomalous V^2, a mediastinal lingular artery, or a lingular vein draining into the inferior pulmonary vein, each of which may result in surgical complications should they fail to be appreciated.

The use of 3D-CT imaging furthermore allows for new types of analysis such as the relationship between lung volume and segmental anatomy (19) or the spatial relationship between intersegmental planes and intersegmental veins (20). Mimae *et al.* reported that the main root of the intersegmental vein (V^3a+b) between the upper and lingular divisions was always located in the upper division, whereas the root of the intersegmental vein (V^6b+c) between S^6 and basal segments was always located in the basal segment; it is important to know that intersegmental veins are not always located on the intersegmental plane when dividing the lung parenchyma along these intersegmental veins (20).

Also, several 3D-CT imaging studies have enrolled a large number of patients within a very short amount of time, some including more than 1,000 cases and others occasionally exceeding 5,000 cases (17,21–23). Such large-scale analyses would be difficult in a cadaveric study. Furthermore, classifying all cases into diverse anatomical categories with 2D images alone would also be an immensely complicated task. Accordingly, the volume, speed, and rigor at which complex anatomic studies may be conducted and analyzed using 3D imaging provides distinct advantages over studies using cadaveric specimens or 2D images alone.

General anatomy of the lung

In 2010, Akiba *et al.* analyzed variations of the pulmonary vein using 3D-CT images (Table 2) (24). They reported that most patients had the expected anatomy (98% of the left side and 86% of the right side). Common ostia were more frequent on the left side than on the right side (33% *vs.* 13%); the middle lobe drained directly into the left atrium or inferior pulmonary vein in 11% of patients; and the right inferior pulmonary vein often divided immediately at the root in 23% of patients. Fourdrain *et al.* also analyzed variations of the pulmonary arteries and veins (25,26). For pulmonary veins, 36% of patients had variations, and variations were more frequent on the right side than on the left side. The most frequent right-sided variation was the existence of three separate pulmonary veins, whereas the most frequent left-sided variation was the existence of a single pulmonary vein. Shiina *et al.* also analyzed variations of the pulmonary vein in the right upper lobe (RUL), right middle lobe (RML), right lower lobe (RLL), and left upper lobe (LUL) and reported that the incidence of variations ranged from 2.6% to 15.3%, but found no variants in the left lower lobe (LLL). They emphasized the importance of variations that could be critical during lung resection, such as anomalous V^2, V^6, RML veins, and lingular veins (27).

Anatomy of the right lobes

In 2015, based on 3D-CT angiography and bronchiography (3D-CTAB), we analyzed the anatomical variations of RUL in more detail and compared data with those in previous cadaveric studies (Table 2, Figures 2,3) (28). Although the incidence of variations in pulmonary arteries was similar, there were differences in the incidence of variations in veins and bronchi, such as the B^1- or B^2-defective patterns. Zhang *et al.* later studied the B^1-defective type in more detail, and additionally analyzed variations in vascular patterns (38). Based on anatomical data, we further created a simplified model of segmental anatomy to guide surgeons while performing segmentectomies (39,40). Our aim was to classify the wide-variety of segmental anatomy into several specific patterns, allowing surgeons to perform segmentectomies with a pattern-based approach. Zhang *et al.* also created a simplified anatomical model for the left upper division which can be considered to be the counterpart of the RUL (41).

Interestingly, some have studied the RUL anatomy by analyzing anatomical structures bilaterally or by taking into account lung volume as a factor for classification. Wang *et al.* compared the superior pulmonary veins bilaterally and proposed a uniform classification that could be applicable for both upper lobes, that is, classifying the veins into central, semi-central, and non-central types (22). Chen *et al.* included segmental lung volume analyzed by 3D imaging as a factor to determine the "dominant pulmonary segment" of the RUL and subsequently determined whether segmental lung volume could be correlated to anatomical variations (19). Other studies analyzed more specific features of the RUL such as the quadrivial pattern bronchus (42), the V^2a intersegmental vein (43), the right top pulmonary vein (44), or Boyden's triad (21,23,45).

In 2017, we subsequently reported on the segmental anatomy of the RML and RLL (Table 2, Figure 3) (29). Pulmonary bronchi and vessels of the RML and S^6 were classified according to the number of stems. Bronchi and pulmonary arteries of S^7 and basal segments were classified by branching patterns. Also, the subsuperior segment (or S*), which is an independent segment between S^6 and S^{10}, was identified in 20.4% of cases. Studies further analyzed the subsuperior segment in more detail, not only on the right side but also bilaterally (16–18).

Anatomy of the left lobes

Between 2020 and 2022, several studies evaluated the LUL anatomy, each using slightly different classification systems (Table 2, Figure 3) (30–33). Isaka *et al*. also analyzed the relationship between branching patterns of bronchi, arteries, and veins, finding a significant correlation between arterial and bronchial branching patterns as well as between arterial and venous branching patterns (46). As previously mentioned, Zhang *et al*. classified the veins of the left upper division into simplified models that can be used during segmentectomies (41). Additional studies also focused on the lingular artery, with one study suggesting that the mediastinal lingular artery might originate from the variation of B^3, and that the presence of a mediastinal lingual artery also influences the venous pattern of the left upper division (47,48).

In 2020, Maki *et al*. reported the anatomy of the LLL (Table 2, Figure 3) (34). They also reported rare variations such as B^7 with independent branching from the basal bronchi; subsuperior bronchus (B*); or an extrapericardial common trunk of the left pulmonary veins. Liu *et al*. proposed a classification for the mediastinal basal artery, which is a pulmonary artery that branches from the proximal part of the left pulmonary artery between the left main bronchus and the left superior pulmonary vein, proceeding directly into the lower lobe (49). The study by Maki *et al*. also included one case of a mediastinal basal artery that branched within the pericardium (34).

Interlobar vessels

Some studies have analyzed the variations of interlobar vessels (Table 2). Information on interlobar vessels would be important for surgeons when identifying these vessels during anatomical lung resection or when dissecting the lung fissure in patients with incomplete lobulation. Wang *et al*. classified the right interlobar arteries according to the order and number of branches of the RML artery and A^6 (35). Xu *et al*. classified the general morphology of the right interlobar veins and reported that interlobar veins hidden by an incomplete upper oblique fissure were most vulnerable to accidental injury; a diameter larger than 2.4 mm for the oblique fissure interlobar vein type or less than 2 mm for the mediastinal interlobar vein type was also associated with a higher risk of injury (36). Murota *et al*. also classified left-side interlobar arteries (37).

Limitations of 3D imaging and development of 3D imaging software

Despite the advantages and contribution to our current understanding of lung anatomy as detailed above, current 3D-CT imaging has its limitations. For example, small blood vessels that are visible on conventional 2D images may not always be reconstructed in 3D-CT images. In our previous study, small vessels with a diameter of less than 1.5 mm were missed on 3D-CT images when compared to intraoperative views (28). For a better identification of small anatomical structures, observing both 3D-CT images and thin-section CT images is equally important. There will always be some inherent difference between 2D images, 3D-CT reconstructed images, and intraoperative views. Vessels that were preoperatively overlooked by 2D or 3D images might only be recognized intraoperatively.

Therefore, feedback from actual intraoperative findings is important to further refine 3D-CT reconstruction methods. Use of 3D-CT images could also be limited by other factors including limited availability of 3D reconstruction software; inadequate conditions during CT examination; and the presence of tumors or atelectasis obstructing bronchi, impeding vascular flow, or obscuring peripheral anatomy. To overcome these limitations, numerous imaging software platforms have been developed and optimized, including Ziostation 2 (Ziosoft Inc.), REVORAS (Ziosoft Inc.), Synapse Vincent (Fujifilm), IQQA-Lung (EDDA Technology), Deepinsight platform (Neusoft Group Ltd.), Mimics software (Materialise), PV-iCAS (PVmed), and the list continues to grow (19,21,28,33,44,45,48). Until now, the prerequisite for 3D imaging of pulmonary vessels was the availability of contrast-enhanced CT images. However, 3D imaging software now allows for 3D reconstruction of pulmonary vessels from non-enhanced CT data (50–53).

Conclusions

We reviewed here key features of 3D-CT imaging of the lung and presented results from representative anatomical studies. Such studies have led to new or modified classification systems, shed light on lung anatomy from a useful surgical viewpoint, and enabled us to analyze lung anatomy with a focus on particular anatomical features. 3D-CT images also allow for enhanced pre- and intra-operative simulation, improved surgical safety, enhanced educational utility, and the capacity to perform large-scale anatomical studies in shorter time frames. A decade has passed since the initial reports on 3D-CT image-guided lung resection (54–59) and 3D-CT imaging has become widely implemented with results of prospective multicenter studies now being reported (60). The current surge of 3D-CT imaging analysis shows that the field is still growing, with the technology continuing to improve and now even being combined with virtual reality and artificial intelligence (61,62). Future studies using these new and innovative methodologies will continue to refine our understanding of lung anatomy while enhancing our ability to perform safe and effective surgical resections.

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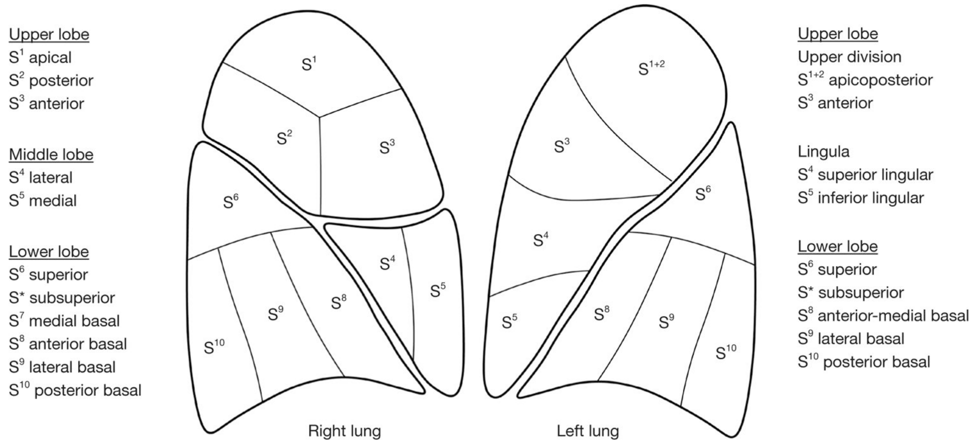

Figure 1.

Schema and nomenclature of bronchopulmonary segments. The medial basal segment (S^7) and subsuperior segment (S*) are not depicted in the schema.

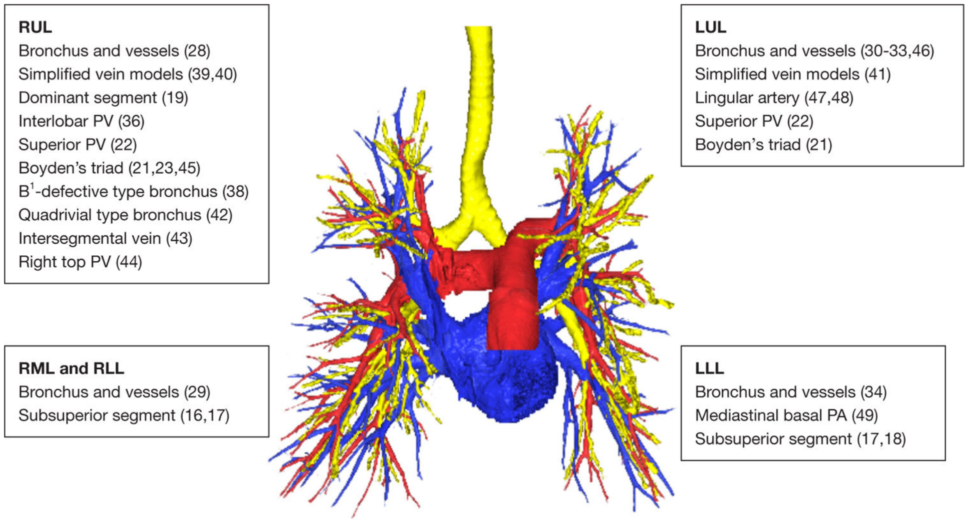

Figure 2.

Anatomical analyses of the lung based on 3D-CT imaging. Anatomical features analyzed by 3D-CT imaging are grouped according to lobes with references in parenthesis. RUL, right upper lobe; RML, right middle lobe; RLL, right lower lobe; LUL, left upper lobe; LLL, left lower lobe; PV, pulmonary vein, PA, pulmonary artery.

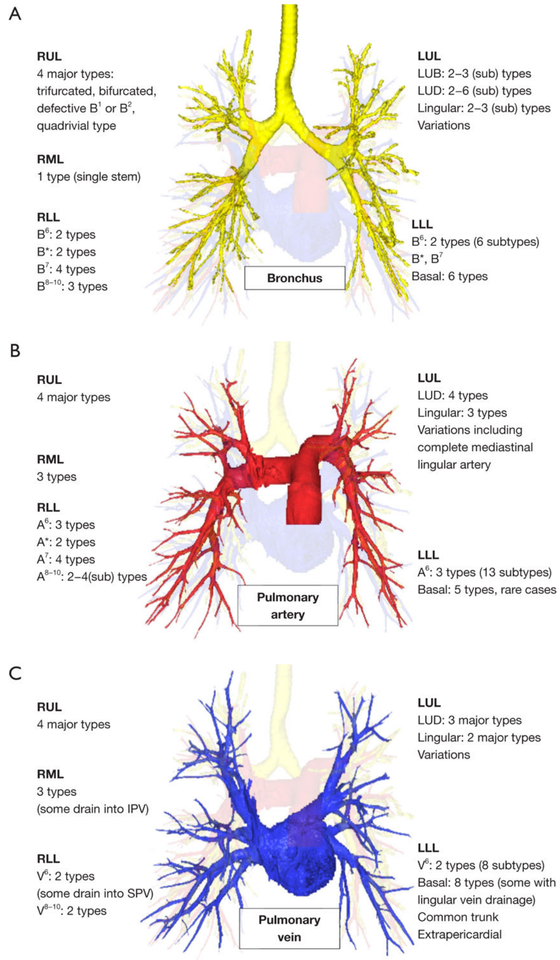

Figure 3.

Anatomical classifications and subtypes of the lung based on 3D-CT images. Overview of subtypes for (A) bronchus, (B) pulmonary artery, and (C) pulmonary veins according to analyses. For clarity, the number of types and subtypes have been simplified in some cases and the reader should refer to the original manuscript for a detailed classification. RUL, right upper lobe; RML, right middle lobe; RLL, right lower lobe; LUL, left upper lobe; LLL, left lower lobe; LUB, left upper bronchus; LUD, left upper division; B*, bronchus of subsuperior segment; A*, artery of subsuperior segment.

Table 1

Features of 3D-CT imaging in lung

- Better recognition of anatomical structures compared to two-dimensional images
- Quick and intuitive recognition of the anatomy and anomalies
- Pre- and intra-operative simulation
- Improved surgical safety
- Enhanced educational utility
- New types of analyses involving lung volume or lung parenchyma
- Large-scale studies with short study times (>1,000 cases)

3D, three-dimensional; CT, computed tomography.

Table 2

Details of lung anatomy analyzed by 3D-CT imaging

Anatomical features	Authors (ref.)	Bronchus	Pulmonary artery	Pulmonary vein
Lung in general	Akiba *et al.* (24)	N/A	N/A	Common ostia Variations of venous drainage
	Fourdrain *et al.* (25,26)	N/A	Number of branches, frequency, and variations in all lobes	Right side: 6 types Left side: 4 types
	Shiina et al. (27)	N/A	N/A	Anomalous drainage of right $V^2/V^3/V^6$ and left lingular veins
RUL	Nagashima *et al.* (28)	4 major types: trifurcated, bifurcated, defective B^1 or B^2, quadrivial type	4 major types	4 major types
RML	Nagashima *et al.* (29)	1 type (single stem)	3 types	3 types (some drain into IPV)
RLL	Nagashima *et al.* (29)	$B^6/B^*/B^7/B^{8-10}$: 2/2/4/3 types	$A^6/A^*/A^7$: 3/2/4 types A^{8-10}: 2 major types (4 subtypes)	V^6: 2 major types (some drain into SPV) V^{8-10}: 2 major types (5 subtypes)
LUL	Deng *et al.* (30)	2 types (8 subtypes)	3 types (10 subtypes) of variations	2 types (5 subtypes) of variations
	Fan *et al.* (31)	LUD: 4 types	LUD: 4 types	LUD: 3 types
		Lingula: 3 types	Lingula: 3 types	Lingula: 2 types
		Uncommon variations	Uncommon variations	Uncommon variations
	Maki *et al.* (32)	LUB: 2 major types	2 types according to lingular artery (15 subtypes)	LUD: 3 major types (13 subtypes)
		LUD: 2 major types (4 subtypes) lingula: 2 types (1 subtype) rare variations	Complete mediastinal lingular artery and rare variations	Lingula: 2 major types (8 subtypes)
	He *et al.* (33)	LUB: 2 types (3 subtypes) LUD: 2 types (6 subtypes) lingula: 2 types (3 subtypes)	N/A	N/A
LLL	Maki et al. (34)	B^6: 2 types (6 subtypes) Basal bronchus: 6 types	A^6: 3 types (13 subtypes) Basal artery: 5 types, rare cases	V^6: 2 types (8 subtypes) Basal vein: 8 types and lingular vein draining into the LLV
		B^*, B^7		Common trunk, extrapericardial
Interlobar vessels	Wang *et al.*, Xu *et al.*, Murota *et al.* (35–37)	N/A	Right side: 4 types (15 subtypes) Left side: 7 types (85 subtypes)	Right side: 2 major types (30 subtypes)

For clarity, the number of types and subtypes have been simplified in some cases and the reader should refer to the original manuscript for a detailed classification. 3D, three-dimensional; CT, computed tomography; RUL, right upper lobe; RML, right middle lobe; RLL, right lower lobe; LUL, left upper lobe; LLL, left lower lobe; LUD, left upper division; LUB, left upper bronchus; PV, pulmonary vein; SPV, superior pulmonary vein; IPV, inferior pulmonary vein; LLV, left lower vein; N/A, not assessed; ref., references.