New Findings on the Three-Dimensional Anatomical Relations between the Bronchi and Pulmonary Blood Vessels at the Pulmonary Hilum

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During the 1940s, considerable knowledge was acquired about the anatomy of pulmonary segments, and anatomical terms were proposed and have been widely accepted. In recent years, minimally invasive and thoracoscopic segmentectomy has been performed with a versatile sublobar resection approach on patients with early peripheral lung cancer, metastatic lung tumors, and undiagnosed nodules. The three-dimensional (3D) anatomy of the bronchi and the pulmonary vessels has also been studied in individual patients. Three-dimensional models of the bronchi and pulmonary vessels were prepared using homemade software from computed tomograms (CT) of the chests of patients scheduled to undergo surgical procedures. Using these models, the authors examined the 3D positional relationships of the segmental broncho-arterial triangle (SBAT) created by three points defined by the origins and courses of the bronchi and the pulmonary arteries, which are located apart from each other at the pulmonary hilum, and the segmental pulmonary veins (SPV), which run near the SBAT. In the left and right upper lobes, many branches of the pulmonary arteries and parallel bronchi in subsegments were widely separated at the origin of the pulmonary hilum, creating a relatively large SBAT. However, as an exceptional case, an SPV passed through an SBAT in only one of 158 patients. To our knowledge, no similar findings have been documented previously. Our findings could help to determine resection surfaces for thoracoscopic segmentectomy in the future, and provide new insights into the 3D anatomy and development of the lung.

Key words: three-dimensional; anatomy; development; bronchi; pulmonary artery; pulmonary veins
TABLE 1. Anatomical Abbreviations of Lung Segments, Segmental Bronchi, Segmental Pulmonary Arteries, and Segmental Pulmonary Veins

| Name                       | Abbreviation |
|----------------------------|--------------|
| Segment                    | S            |
| Bronchus                   | B            |
| Pulmonary artery           | A            |
| Pulmonary vein             | V            |
| Apical segment, a: apical ramus, b: anterior ramus | S₁, S₂, B₁, B₂, A₁, A₂, V₁, V₂ |
| Posterior segment, a: posterior ramus, b: horizontal ramus | S³, B³, A³, V³ |
| Anterior segment, a: lateral ramus, b: medial ramus | S⁴, B⁴, A⁴, V⁴ |
| Upper sub-subsegment ramus of B₃a and A₃a | B₃ai, A₃ai |
| Lower sub-subsegment ramus of B₃a and A₃a | B₃a, A₃a |
| V. posterolateralis (between S₂a and S₂b) | V₂b, V₂c |
| V. horizontalis (between S₂b and S₃a) | V₃ |
| V. terminalis (below S₂a) | V₃t |
| V. anterior (below B₃b) | V₃b |
| V. lateralis (between S₃a and S₃b) | V₃d |
| Subapical segment artery   | A₆           |

vessels (Boyden, 1954; Yamashita, 1978). The development of computed tomography (CT) has allowed many anatomical analyses to be performed (Osborne et al., 1984; Asai et al., 2005), and three-dimensional (3D) image processing has been realized and used for surgery (Matsumoto et al., 2011; Oizumi et al., 2011; Ikeda et al., 2013). Segmentectomy is now performed to resect early peripheral lung cancer, metastatic lung tumors, and undiagnosed nodules in addition to the conventional indications of pulmonary infection (Okada et al., 2007; Schuchert et al., 2012). Thoracoscopic surgery has been performed with the help of 3D images generated by high-resolution 3D CT (HRCT) (Oizumi et al., 2011; Kanzaki et al., 2011, 2013), and attention has again focused on the 3D anatomical structures of pulmonary segments. The authors closely inspected 3D models of the bronchi and pulmonary blood vessels prepared before thoracoscopic anatomical sublobar resection (TASLR), including procedures such as left upper division resection, lingular segmentectomy, segmentectomy, and subsegmentectomy (Kanzaki et al., 2011, 2013), to determine whether a segmental pulmonary vein (SPV) ever passed through the segmental bronchoarterial triangle (SBAT); the SBAT is created by the origins of the segmental bronchi and the segmental pulmonary arteries and the point where these structures start to course in parallel at the hilum. The findings were then confirmed at surgery. In addition, the authors discussed the embryonic basis for the findings and its clinical significance in thoracoscopic surgery.

METHODS

Since 2005, the authors have created three-dimensional (3D) models of the bronchi and pulmonary blood vessels from preoperative HRCT images using Metasequoia® (http://www.metaseq.net/metaseq/), a 3D modeling program prepared with the homemade software CTTRY, of patients scheduled to undergo TASLR (Onuki, 2009; Kanzaki et al., 2011, 2013). In patients scheduled for TASLR of the upper lobe from January 2008 through February 2013, the authors closely examined whether an SPV passed through a SBAT using these models, and as far as possible confirmed the results from the models during surgery. In addition, the authors examined whether an SPV passed through the SBAT in the figures depicting the bronchi and the pulmonary arteries, and the veins of the left and right upper lobes, in textbooks and other materials written by Boyden (1945, 1954) and Yamashita (1978). Because there are no internationally accepted symbols for describing subsegments, Yamashita’s (1978) abbreviations for subsegments were used in the figures and text of this report (Table 1).

This study was approved by the institutional ethics committee of Tokyo Women’s Medical University (no. 2760). The patients received both oral and written information regarding the procedure.

RESULTS

TASLR was performed from January 2008 through February 2013 in our department on 57 patients with lesions in the right upper lobe and on 101 patients with lesions in the left upper lobe. For all patients, the authors preoperatively prepared 3D models of the bronchi and blood vessels using CTTRY and examined the 3D structures of the lung on Metasequoia® to confirm the positional relationships between the SBAT and SPVs; surgery was then performed. The surgical procedures were as follows: left upper segmentectomy on 29 patients, left lingular segmentectomy on 15, multiple segmentectomy on three, segmentectomy on 75, multiple sub-segmentectomy on 19, and subsegmentectomy on 17. In two patients, hilar lymph-node metastasis was confirmed intraoperatively and upper lobectomy was performed. The postoperative diagnoses were lung adenocarcinoma in 89 patients, squamous-cell carcinoma in 11, other types of lung cancer in four, metastatic lung tumors in 34, infectious granuloma in seven, benign tumors in two, arteriovenous malformation in one, bronchiectasis in one, and a non-specific inflammatory mass in eight. The 3D anatomy of the bronchi and the pulmonary arteries and veins in the segments and the subsegments varied considerably. There were various SBATs defined by the origins of the subsegmental bronchi and subsegmental pulmonary arteries, and the point where these structures started to course in parallel. In the right upper lobe, the areas of SBATs created by the bronchi and the pulmonary arteries of 2b, 2a, and 3b were relatively large (Fig. 1). In the left upper lobe, the areas of SBATs created by the bronchi and pulmonary arteries in the presence of a mediastinal lingular pulmonary artery, or SBATs created by B⁴, C and A⁴, C were large. However, SPVs never passed through any of these SBATs except in one patient, described below. In materials prepared by Boyden, the number of figures...
of the bronchi and the pulmonary arteries and veins were 22 and two for the right upper lobe and 20 and two for the left upper lobe (Boyden, 1945, 1954). In materials prepared by Yamashita (1978), the numbers of figures of the former were 13 and 15, respectively. None of these figures clearly showed the passage of an SPV through an SBAT.

**Case Illustration**

A 78-year-old woman had an abnormal shadow on her chest X-ray film. Examination revealed a mass shadow in the right upper lobe (Fig. 2A). Lung cancer was suspected, and the patient was referred to our department. The maximum standardized uptake value on positron emission tomography was 1.2. Before operation, 3D models of the bronchi and pulmonary blood vessels were prepared. The B1, B2, and B3 bronchi in the right upper lobe were bifurcated, and the mass was judged to be located in S3a. V2 was found to pass through an SBAT created by B3 and B3a. The anatomical characteristics were confirmed on the 3D models of the bronchi and blood vessels, and S3 segmentectomy was scheduled on the basis of tumor size and location (Fig. 2B). The operative findings confirmed that (1) V2 passed through the SBAT created by B3 and B3a (Figs. 2C,D) and (2) the anatomical configuration was consistent with that of the 3D models of the bronchi and blood vessels. Eventually, S3 segmentectomy was performed as scheduled. Pathological diagnosis showed that the resected specimen was a non-specific inflammatory mass. The patient was discharged on postoperative day 9.

During surgery, the upper and middle lobes were divided with an automatic stapling device, and V3b and V3d were transected. A3b was then transected. The pulmonary arteries A3 and A4, the basal artery, and V2 were clearly seen in the region between the upper and middle lobes (Fig. 2C). The transection site of A3b was widened to expose B3b, and the region was pulled with a suture to visualize B3a. A3a was then transected, exposing V2c, V2b, and V2t.

**DISCUSSION**

During TASLR, there are many opportunities to perform segmentectomy by sharply dividing apparent
inter-segments from the visceral pleura along an inflation-deflation line towards the hilum using an electronic scalpel or an ultrasonic coagulating device, with the segmental pulmonary veins (SPV) as an anatomical guide (Ramsay, 1949). At that time, there is a low risk of transecting the subsegmental bronchi or arteries, given that the wrong plane is seldom selected, because it is extremely rare for an SPV to pass through an SBAT. In the lower lobes, the origins of the segmental bronchi and segmental arteries are close to each other, and there is little space for pulmonary veins to pass between these structures. In the upper lobes, however, the origins of the subsegmental bronchi and corresponding arteries are often separated by a considerable distance. It is spatially possible for an SPV to pass through an SBAT. However, an

**Fig. 2.** An exceptional patient in whom the pulmonary veins pass through the triangle created by B³a and A³a. **A:** On the computed tomogram (CT) of the patient, a mass shadow was found. **B:** A three-dimensional (3D) model of the bronchi and the pulmonary arteries, prepared using the homemade software CTTR, of the patient whose pulmonary veins passed through the segmental bronchoarterial triangle (SBAT), viewed laterally and slightly caudally. The bronchi are yellow, the pulmonary arteries are red, the pulmonary veins are blue, and the mass is shown in black. Usually, the bifurcation of A³a is proximal to A³b. However, in this patient, A³a arose from the same site as A⁴⁵ ᵄ ᵄ and was then immediately followed by the bifurcation of A⁶, forming the basal segmental artery. V² passed through the SBAT created by B³a and A³a (green region). **C:** The upper and middle lobes of the right lung were separated (broken blue line), and V³b and A³b were then transected. V³ passed through the green triangle, showing the SBAT created by B³a and A³a. **D:** A³a was transected, exposing V³ distally. B³b was pulled with a suture. The green triangle shows the SBAT created by A³a (transsection) and B³a. V⁴, which gave rise to V³b, V³c, and V³t, passed through the SBAT. All abbreviations are explained in Table 1.
SPV passed through an SBAT in the upper lobe of only one of our 158 patients. In future, knowledge that "generally, no SPV passes through an SBAT" could allow surgeons to decide the resection plane for TASLR. Boyden (1954) and Yamashita (1978) described the detailed anatomical characteristics of the lung but failed to make a general statement that "no SPV passes through an SBAT". If this does not become general knowledge, exceptional cases including the case reported in this study would be difficult to identify. The authors therefore believe that this study provides new knowledge about the anatomy of the lung.

It has been reported that the branching pattern of the bronchi is highly stereotyped and essentially identical among inbred mouse strains during the "pseudoglandular stage" between embryonic days E9.5 and E16.5 (Metzger et al., 2008). Although three models have been proposed to explain how the vasculature develops in the lung (deMello et al., 1997; Hall et al. 2000; Parera et al., 2005), all accounts maintain that lung vascular development is concurrent with the development of the bronchi. At that time, the bronchi and blood vessels are spatially very close to each other. Nevertheless, in the adult lung, the point of origin of the bronchi on the bronchial tree and the territory usually ventilated by individual bronchi are often inconsistent with the prevailing pattern (Boyden, 1954; Yamashita, 1978). Weibel and Gomez (1962), who described the fractal branching pattern of the airways, reported that the total number of airway generations varies markedly among parts of the lung. The 3D anatomical variations of the bronchi and pulmonary blood vessels are diverse, and the pulmonary arteries of the same segment often arise from branches in different locations. Taking these characteristics into account, the authors proposed the following hypothesis to explain why a large SBAT was formed and why no SPV was able to pass through it. In the early stage of lung development, regularly branching bronchi during the "pseudoglandular stage" and pulmonary blood vessels developing in association with the bronchi increase in caliber in accordance with "the principle of minimum resistance and minimum mass" (Weibel and Gomez, 1962) and undergo remodeling. More space is required for the passage of branches in the upper lobes than in the middle and lower lobes, leading to severe remodeling and structural changes. At birth, the origins of the segmental bronchi and the segmental pulmonary arteries might

**Fig. 3.** A topologically simplified developmental model of the proximal conductive zone of the lung. **A**: During the pseudoglandular stage, thin future pulmonary arteries and veins adhere to the regularly branching airway buds. The pulmonary veins are located at the lateral sides of the bronchi and pulmonary artery sheath. **B**: Branches of a given generation can become segmental branches, subsegmental branches, or sub-subsegmental branches in association with subsequent branch growth. In some segments, the branches of bronchi arising from the main bronchi during early development sometimes re-merge, forming a single segment \(B^2a + B^2b\). Because of this phenomenon, pulmonary arteries with origins in different locations can merge together in the same segment. **C**: Despite such severe remodeling, the pulmonary veins are located at the lateral sides of the bronchi and the pulmonary arteries. Because this topological positional relation is maintained, segmental pulmonary veins seldom pass through a segmental broncho-arterial triangle. The blue transparent zone indicates a pulmonary vein can run though.
be apart from each other, creating a large SBAT. However, despite such dynamic remodeling, the pulmonary veins are located laterally to the bronchi and the pulmonary arteries in nearly everyone, although it has been reported that the early blood vessels in the lung are rather undifferentiated in their arterial versus venous lineage (Schwarz et al., 2009). Because this topological and positional relationship is maintained, it is hypothesized that SPVs are unable to pass through an SBAT (Fig. 3A-C).

In our cases, an SPV passed through an SBAT in one of the 158 subjects. In this particular patient, A2\textsuperscript{b} and A4\textsuperscript{1–5} arose from the main pulmonary artery, and the pulmonary artery gave rise distally to S\textsuperscript{3}a\textsubscript{i}. This mild but extremely rare abnormal bifurcation of the pulmonary artery was not described by Boyden or Yamashita. If this patient had undergone segmentectomy for resecting a mass located in S\textsuperscript{2}, and the transection plane ran from along the veins from the hilum, A\textsuperscript{3}a\textsubscript{i} would unavoidably have been transected. Because it is difficult to visualize the entire lung during thoracoscopic surgery, intersegmental transection in the lung at the hilum, using the intersegmental pulmonary veins as an anatomical guide, carries the risk of mistakenly transecting the subsegmental bronchi and pulmonary arteries in such patients. The frequency of these exceptional cases is unclear, and this anatomical abnormality was difficult to detect on conventional CT images. Therefore, 3D models of the bronchi and pulmonary blood vessels should be prepared for each individual patient to ensure that TASLR can be performed accurately.

**CONCLUSIONS**

This study investigated the anatomical positional relationships of the bronchi and pulmonary blood vessels using 3D models to enable TASLR to be simulated preoperatively. In nearly all patients, no SPV passed through an SBAT. As an exception, in only one of 158 patients, an SPV was found using 3D models of the bronchi and pulmonary blood vessels to pass through an SBAT in the upper lobe. To our knowledge, no similar findings have been documented previously. In the future, our findings may be useful for determining resection surfaces for thoracoscopic segmentectomy and they provide new insights into the 3D anatomy and development of the lung.

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