Progress in three-dimensional computed tomography reconstruction in anatomic pulmonary segmentectomy

Zhe Wu | Zhangfeng Huang | Yi Qin | Wenjie Jiao

Department of Thoracic Surgery, the Affiliated Hospital of Qingdao University, Qingdao, China

Correspondence
Wenjie Jiao, Department of Thoracic Surgery, the Affiliated Hospital of Qingdao University, 16 Jiangsu Rd, Qingdao 266003 China. Email: jiaowj@qduhospital.cn

Abstract
The number of minimally invasive surgeries, such as video-assisted thoracoscopic surgery and robot-assisted thoracoscopic surgery, has increased enormously in recent years. More and more relevant studies report that anatomic pulmonary segmentectomy has the same effect as traditional lobectomy in the surgical treatment of early stage non-small cell lung cancer (diameter less than 2.0 cm). Segmentectomy requires sufficient knowledge of the location of the pulmonary nodules, as well as the anatomy of the target segments, blood vessels, and bronchi. With the rapid development of imaging technology and three-dimensional technology, three-dimensional reconstruction has been widely used in the medical field. It can effectively assess the vascular branching patterns, discover the anatomic variations of the blood vessels and bronchi, determine the location of the lesion, and clarify the division of the segments. Therefore, it is helpful for preoperative positioning, surgical planning, preoperative simulation and intraoperative navigation, and provides a reference for formulating an individualized surgical plan. It therefore plays a positive role in anatomic pulmonary segmentectomy. This study reviews the progress made in three-dimensional computed tomography reconstruction in anatomic pulmonary segmentectomy.

KEYWORDS
lung cancer, pulmonary segmentectomy, three-dimensional computed tomography, three-dimensional reconstruction

INTRODUCTION
Lung cancer remains the leading cause of cancer and mortality in China and worldwide.1,2 Although the treatment of lung cancer is increasingly diverse, surgical resection is still the mainstay option.3,4 Minimally invasive surgeries such as video-assisted thoracoscopic surgery (VATS) and robot-assisted thoracoscopic surgery (RATS) have achieved remarkable results in the treatment of early stage non-small cell lung cancer (NSCLC),5–7 and have been gradually promoted.

Segmentectomy for early stage lung cancer has achieved a good long-term prognosis while maximizing removal of the lesion and protecting lung function.8,9 According to the meta-analyses results of Zhang et al.10 and Bao et al.11 anatomic pulmonary segmentectomy combined with systematic hilar and mediastinal lymph node dissection can achieve a satisfactory result for stage I NSCLC patients with tumors less than 2 cm. Segmentectomy requires the surgeon to have a clear understanding of the location of the target tumors, as well as the anatomy of the target lobes, segments, bronchi, arteries and veins.

With the development of imaging technology, such as multidetector computed tomography (MDCT) and three-dimensional computed tomography bronchography and angiography (3D-CTBA), two dimensional (2D) images can be converted into three dimensional (3D) images.12,13 In order to reduce the intraoperative risks, accurately locate the lesions, improve the safety of surgery and achieve a precise resection, 3D reconstruction came into being and developed rapidly, especially in thoracic surgery. In this study, we review the progress made in 3D computed tomography (CT) reconstruction in anatomic pulmonary segmentectomy.

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ANATOMIC PULMONARY SEGMENTECTOMY

Segmentectomy is defined as resection of one segment or one segment and its additional adjacent segment. From the technical aspect, segmentectomy is further categorized into simple or complex: resection of the right or left superior segment of the lower lobe (segment 6), the left superior, and the lingular segment is defined as simple. Complex segmentectomy is defined as resection of a segment that has more than one intersegmental plane. Even for certified thoracic surgeons, two or more intersegmental planes make segmentectomy technically more difficult. Churchill and Belsey first reported the application of segmentectomy for the treatment of pulmonary tuberculosis and atelectasis in 1939. Le Roux first reported the use of segmentectomy for the surgical treatment of primary lung cancer in 1972. Now segmentectomy has been gradually popularized and has been shown to achieve good results. Dai et al. reported that in patients with peripheral NSCLC of less than 2 cm, segmentectomy and lobectomy were comparable in the short-term clinical outcomes, and produced comparable symptom burden and functional impairment during the early postoperative period. Chan et al. showed that in the setting of clinical T1cN0M0 NSCLC, anatomic segmentectomy was not associated with significant differences in recurrence-free or overall survival at 5 years. Wen et al. reported that segmentectomy achieved similar recurrence-free and overall survival compared with lobectomy for patients with clinical N0 invasive lung adenocarcinomas of no more than 2 cm. In addition, segmentectomy was found to help preserve more pulmonary function than lobectomy. It is worth mentioning that the ongoing JCOG0802/WJOG4607L, JCOG1211, and CALGB140503 trials will disclose the influence of segmentectomy for patients with early-stage NSCLCs that are small peripheral tumors based on preoperative high-resolution CT findings about preserved pulmonary function and long-term prognosis.

THREE-DIMENSIONAL RECONSTRUCTION TECHNOLOGY

Three-dimensional technology has previously been widely used in the medical field. Three-dimensional reconstruction means that the 2D image information such as CT value is extracted and segmented by the software and with the help of the supplementary judgment of the bronchus and blood vessels by the doctor, so as to build a 3D image of the lung. Three-dimensional reconstruction technology began in the 1970s. Tomasi and Kanade completed the first image-based 3D reconstruction system in 1992. Scholars then began to apply 3D reconstruction to determine the relationship between tumor and blood vessels, and identify pulmonary vessels and bronchi. Now, 3D reconstruction is used in thoracic surgery. Take Materialise's interactive medical image control system (Mimics) (developed by Materialise Nv Co., Kingdom of Belgium) as an example. First, after manually confirming the starting point of each segmental pulmonary artery, the computer automatically divides the pulmonary segments according to the distribution of the pulmonary artery system, and divides the pulmonary subsegments according to the starting point of the subsegmental pulmonary artery. Then, the following seed line method is the main method, while the manual extraction is the auxiliary method. The lung parenchyma is extracted to the greatest extent, which combines with the division of pulmonary segments and subsegments to generate the corresponding modules and define the corresponding colors. Next, adjust the CT image to the pulmonary artery window, and divide the whole arterial tree by the seed point method. The venous vascular tree can be divided in the same way. Then, adjust the threshold to the required range of the bronchus, and complete the bronchial reconstruction by the threshold division and the seed point method. Finally, the pulmonary nodules can be divided and reconstructed. Larger nodules can be extracted by the threshold division and the seed point method, while smaller nodules can be extracted manually. The 3D images of the pulmonary nodules and the 3D images of the lung are combined to clearly show the specific location of the nodules and the pulmonary segment or subsegment to which they belong by adjusting the transparency of the 3D images of the lung. The reconstructions of trachea and bronchi, pulmonary lesion, pulmonary vessels and lung are shown in Figure 1–FIGURE 4. The 3D reconstruction model is shown in Figure FIGURE 5.

ADVANTAGES OF THREE-DIMENSIONAL RECONSTRUCTION

Three-dimensional reconstruction can convert 2D images of the pulmonary arteries, pulmonary veins, and bronchi into 3D images of the vascular tree and bronchial tree, clearly showing the structure of the blood vessels and bronchi, effectively assessing vascular branching patterns and discovering the anatomic variations of the blood vessels and bronchi. Three-dimensional reconstruction can show the morphological characteristics of the lesion three-dimensionally, and also clearly display the blood supply inside and around the lesion, helping physicians to make more accurate judgments of the nature of the lesion. Three-dimensional reconstruction can accurately identify the normal anatomic structure, clarify the division of the pulmonary segments, determine the location of the lesion and the positional relationship with the target segment, which is helpful for the complete resection of the target segment and the guarantee of the surgical margins.

Studies have indicated that the 3D images can be rotated freely and visualized interactively from any angle, which can directly measure the distance and positional relationship between the blood vessels, bronchus and the lesion, perform intraoperative navigation with the assistance of related software, avoid the unnecessary dissection of...
lung tissue, and save intraoperative time to find and discern the segmental pulmonary venous vessels, thus shortening the operation time, \(^{34}\) reducing the amount of bleeding during the operation, and improving the success rate of the operation. Three-dimensional reconstruction is helpful for preoperative positioning, surgical planning, preoperative simulation and intraoperative navigation, and provides a reference for formulating an individualized surgical plan. \(^{35–37}\)

\section*{THREE-DIMENSIONAL RECONSTRUCTION IN ANATOMIC PULMONARY SEGMENTECTOMY}

Scholars have reported the use of thin-layer CT data for processing 3D-CT models for lobectomy and segmentectomy since 2001. \(^{38,39}\) Three-dimensional reconstruction has been gradually applied to anatomic pulmonary segmentectomy and achieved satisfactory results.
She et al.\textsuperscript{40} reported that in comparison with the 2D group, operative duration shortened significantly, the extent of intraoperative bleeding and postoperative drainage lowered significantly, and chest tube duration shortened significantly in the 3D group. Hemoptysis and pulmonary air leakage (more than 3 days) occurred significantly less frequently in the 3D than in the 2D group. Xue et al.\textsuperscript{41} showed that median operation time for the 3D group was shorter than in the non-3D group. The study indicated that 3D images can be used to reduce the risk of insufficient surgical margins. The guidance of 3D images may enable accurate locate of the lesions and illustrate the variation pattern of the segmental vessels and bronchi. Preoperative 3D simulation can be helpful in precise surgical planning. Liu et al.\textsuperscript{42} reported that compared with the general CT group, intraoperative blood loss significantly decreased operation time and postoperative hospital stay was significantly shortened in the 3D-CT group. The incidence of postoperative

\begin{figure}[h]
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\includegraphics[width=\textwidth]{F3.jpg}
\caption{Pulmonary artery and vein reconstruction}
\end{figure}

\begin{figure}[h]
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\includegraphics[width=\textwidth]{F4.jpg}
\caption{Lung reconstruction}
\end{figure}
hemoptysis in the 3D-CT group occurred lower in the general group, but the differences were not statistically significant. This article shows that 3D-CT and 3D printing for making a preoperative plan have an equivalent effect in thoracoscopic pulmonary segmentectomy for experienced surgeons. Qiu et al. showed that intraoperative bleeding in 3D-reconstruction was significantly lower than in the non-3D group. With regard to complex segmentectomy, the 3D-reconstruction group spent a shorter operation time when compared with the non-3D group. Three-dimensional reconstruction imaging and 3D printed model were both found to have significant advantages in locating nodules and identifying vascular variations. Moreover, this study proposed a preliminary preoperative rating scale to select appropriate patients for 3D reconstruction or 3D printing, which would develop detailed guidelines for the application of this technique in thoracic surgery. Lin et al. reported that patients with preoperative 3D image simulations had fewer relapses than patients without preoperative 3D image simulations, which confirmed the relationship between the tumor and surrounding blood vessels and bronchus and ensured an oncological safety margin. In addition, preoperative 3D simulation may alter the oncological outcomes for patients with clinical stage IA2 NSCLC. Wu et al. reported that 57 patients received segmentectomy assisted by 3D-CTBA, and the surgical results were as follows: duration of surgery, 129.8 ± 16.1 min; blood loss, 48.8 ± 26.2 ml; length of postoperative hospital stay, 6.4 ± 1.3 days. The study concluded that preoperative 3D-CTBA images could clearly and vividly display the targeted structure and the variations of vessels and bronchi. Meanwhile, the application of 3D-CTBA with a virtual 3D surgical margin assisted the surgeon to determine accurate distances and the positional relationship among the tumor, bronchial trees, and the intersegmental vessels. The advantages of the 3D group compared with the non-3D group are shown in Table 1.

Oizumi et al. indicated that 3D-CT could effectively guide thoracoscopic pulmonary segmentectomy and ensure the safety of the operation, especially when difficult pulmonary segmentectomies were performed. Hagiwara et al. concluded that preoperative simulations using 3D-CT for the assessment of pulmonary vessel branching patterns appear to be beneficial for the safe and efficient performance of thoracoscopic pulmonary segmentectomy and for further understanding of the surgical anatomy related to general thoracic surgery. LeMoal et al. indicated that all 3D reconstructions met their expectations: anatomical accuracy (bronchi, arteries, veins, tumor, and the thoracic wall with intercostal spaces), accurate delimitation of each segment in the lobe of interest, margin resection, free space rotation, portability (smartphone, tablet) and time saving technique. The operative planning by 3D CT reconstruction is useful in robot-assisted segmentectomy.

### TABLE 1  The advantages of the 3D group compared with the non-3D group

|                          | 3D group       | Non-3D group   |
|--------------------------|----------------|----------------|
| Operation time (minute)  |                |                |
| Liu et al.41             | 115.5 ± 37.2   | 133.0 ± 35.7   |
| Qiu et al.42             | 116.1 ± 30.7   | 125.1 ± 23.6   |
| She et al.43             | 141.9 ± 29.1   | 160.9 ± 31.5   |
| Xue et al.44             | 111            | 139            |
| Intraoperative bleeding (ml) |              |                |
| Liu et al.41             | 75.1 ± 57.4    | 106.3 ± 70.8   |
| Qiu et al.42             | 20.9 ± 12.2    | 18.2 ± 12.2    |
| She et al.43             | 96.4 ± 47.5    | 131.7 ± 48.5   |
| Postoperative hospital stay (days) |          |                |
| Liu et al.41             | 4.5 ± 1.7      | 5.1 ± 1.8      |
| Complication             |                |                |
| Postoperative hemoptysis  |                |                |
| Liu et al.41             | 2.6% (1/39)    | 13.2% (7/53)   |
| Hemothysis               |                |                |
| She et al.43             | 1.9% (1/51)    | 15.6% (8/51)   |
| Pulmonary air leakage    |                |                |
| She et al.43             | 3.9% (2/51)    | 19.6% (10/51)  |
| Postoperative drainage (ml) |              |                |
| She et al.43             | 425.4 ± 163.5  | 664.7 ± 245.6  |
| Chest tube duration (days) |              |                |
| She et al.43             | 2.7 ± 1.0      | 4.2 ± 1.6      |
| Recurrence               |                |                |
| Lin et al.45             | 2% (2/99)      | 11.5% (21/182) |

### INSUFFICIENCIES OF THREE-DIMENSIONAL RECONSTRUCTION

The application of the 3D reconstruction in pulmonary segmentectomy has been increasing, but it still has some shortcomings. (a) Three-dimensional reconstruction has strict requirements for the 2D images of CT. If the distribution of pixels in the source images is affected by the poor cooperation of patients, artifact, insufficient breathholding,
insufficient air in the distal small airways, or inappropriate injection phase of contrast agent into the human body, there will be errors in the reconstruction of the pulmonary blood vessels and bronchi, which will affect the quality of 3D reconstruction. Therefore, patients are required to cooperate as best as possible during the CT examination. (b) Because the branches of the pulmonary blood vessels and bronchi are more variable, there are still errors in the imaging of the blood vessels and bronchi in 3D reconstruction. Therefore, surgeons should combine the 3D images with the CT images before the operation, and carefully identify and analyze the branches during the operation; at the same time, it also requires further optimization of the 3D reconstruction software. (c) In most cases, adjacent pulmonary segments are interlaced with each other instead of being bounded by a straight line. During the operation, a broken line boundary may appear when searching for the intersegmental plane. It means that the results of 3D reconstruction do not completely reflect the division of the intersegmental plane, and the surgeons need to combine the results of 3D images with the actual intersegmental boundary. (d) During 3D reconstruction, the lung is in a state of expansion and normal anatomic position. However, after intraoperative one-lung ventilation, the affected lung is in a state of collapse and is pulled in multiple directions, which may deviate from the normal anatomic position. There will therefore be a certain degree of differences in the running directions of the pulmonary blood vessels and bronchi in the two different situations. It requires surgeons to place the lung in a relatively normal anatomic position, and combine the 3D images to accurately identify the blood vessels and bronchi. (e) The 3D images still need to be displayed in a 2D window, which lacks a sense of entity. As a result, 3D reconstruction can be combined with 3D printing, virtual reality (VR) or other technologies to make it more convenient for surgeons to view a 3D model and realize the establishment and understanding of the overall space.41 (f) Three-dimensional reconstruction software are difficult to operate, some are expensive or not open to individual users.

**PROSPECT OF THREE-DIMENSIONAL RECONSTRUCTION**

In order to break through the limitation that traditional 3D visualization software can only form the static simulation, Tokuno et al.19 developed research progress map (RPM) software, which can semi-automatically generate virtual dynamic images based on the specific CT data of patients, which can quickly and accurately reflect the dynamic simulation of lung traction, resection and other deformation during the operation, and guide the operation process in real time.

In future, the application of contrast agents with higher contrast, the innovation of image acquisition technology, and the advancement of computer processing software will play a positive role in the development of 3D reconstruction. The combination of artificial intelligence technologies such as 3D printing and virtual reality with 3D reconstruction technology can enhance the surgeon’s overall perception of the target area. Three-dimensional reconstruction technology has a broad application prospect, which can further promote the development of anatomic pulmonary segmentectomy and even thoracic surgery.

**CONFLICT OF INTEREST**
The authors declare no conflicts of interest.

**ORCID**

Zhe Wu [https://orcid.org/0000-0001-6482-1359](https://orcid.org/0000-0001-6482-1359)

Wenjie Jiao [https://orcid.org/0000-0002-2187-4992](https://orcid.org/0000-0002-2187-4992)

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