Turkish Journal of Thoracic and Cardiovascular Surgery 2025;33(3):341-348

ORIGINAL ARTICLE / ÖZGÜN MAKALE

Three-dimensional modeling of bronchovascular anatomy for preoperative planning and intraoperative guidance in uniportal video-assisted thoracoscopic segmentectomy

Uniportal video yardımlı torakoskopik segmentektomide ameliyat öncesi planlama ve ameliyat sırası rehberlik için bronkovasküler anatominin üç boyutlu modellenmesi

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ABSTRACT

Background: This study aim to evaluate the feasibility of three-dimensional (3D) modeling using open-source free software for preoperative planning and intraoperative guidance in uniportal video-assisted thoracoscopic segmentectomies.

Methods: Between October 2020 and November 2023, 50 patients (27 males, 23 females; mean age: 60±11.1 years; range, 34 to 78 years) who underwent uniportal video-assisted thoracoscopic pulmonary segmentectomy with preoperative 3D modeling were retrospectively analyzed. Preoperative 3D modeling was performed using computed tomography with an open-source 3D software program. The virtual models exported to the mobile device were compared with the anatomical structures of the patient intraoperatively. The patients were divided into two groups as simple and complex segmentectomy according to the characteristics of the surgical procedures.

Results: The overall matching success rate of the virtual 3D models with intraoperatively identified bronchovascular structures was 99.27%. The overall variation rate was 36% (n=18) among all patients. There was a significant difference between the two groups in terms of the bronchovascular variation. The bronchovascular variation rate was 11.1% (n=2) in Group 1 and 50% (n=16) in Group 2 (p=0.006).

Conclusion: Three-dimensional modeling using open-source software for preoperative planning and intraoperative guidance is a reliable method for detecting bronchovascular structures of the target segment with high accuracy in uniportal video-assisted thoracoscopic surgery segmentectomy.

Keywords: 3D modeling, segmentectomy, uniportal, video-assisted thoracoscopic surgery.

ÖZ

Amaç: Bu çalışmada uniportal video yardımlı torakoskopik segmentektomilerde ameliyat öncesi planlama ve ameliyat sırası rehberlik için açık kaynaklı yazılım kullanarak üç boyutlu (3D) modellemenin uygulanabilirliği değerlendirildi.

Çalışma planı: Ekim 2020 - Kasım 2023 tarihleri arasında ameliyat öncesi 3D modelleme ile uniportal video yardımlı torakoskopik pulmoner segmentektomi uygulanan toplam 50 hasta (27 erkek, 23 kadın; ort. yaş: 60±11.1 yıl; dağılım, 34-78) retrospektif olarak incelendi. Ameliyat öncesi 3D modelleme bilgisayarlı tomografi kullanılarak açık kaynaklı 3D yazılım programı ile hazırlandı. Mobil cihaza aktarılan sanal modeller, ameliyat sırası hastaya ait anatomik yapılar ile karşılaştırıldı. Hastalar cerrahi işlemlerin özelliklerine göre basit ve kompleks segmentektomi olmak üzere iki gruba ayrıldı.

Bulgular: Sanal 3D modellerin, ameliyat sırası tespit edilen bronkovasküler yapılarla genel eşleştirme başarı oranı %99.27 idi. Tüm hastalar içinde genel varyasyon oranı %36 (n=18) idi. İki grup arasında bronkovasküler varyasyon yönünden anlamlı fark vardı. Grup 1'de bronkovasküler varyasyon oranı %11.1 (n=2) ve Grup 2'de %50 (n=16) idi (p=0.006).

Sonuç: Ameliyat öncesi planlama ve ameliyat sırası rehberlik için açık kaynaklı ücretsiz yazılımla hazırlanan üç boyutlu modelleme, uniportal video yardımlı torakoskopik cerrahi segmentektomide hedef segmente ait bronkovasküler yapıların yüksek doğrulukla tespit edilmesi için kullanılan güvenli bir yöntemdir.

Anahtar sözcükler: 3D modelleme, segmentektomi, uniportal, video yardımlı torakoskopik cerrahi.

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Doi: 10.5606/tgkdc.dergisi.2025.27289

Received: December 21, 2024
Accepted: January 15, 2025
Published online: June 27, 2025

Cite this article as: Gürz S, Şengül A. Three-dimensional modeling of bronchovascular anatomy for preoperative planning and intraoperative guidance in uniportal video-assisted thoracoscopic segmentectomy. Turk Gogus Kalp Dama 2025;33(3):341-348. doi: 10.5606/tgkdc.dergisi.2025.27289.

Lung-sparing surgical techniques have gained increasing importance with the rise in early-stage lung cancer diagnoses and improvements in radiological detection. In this evolving landscape, segmentectomy is becoming more than just an alternative; it's emerging as a key strategy in selected patients.

Recent studies by the Japanese Clinical Oncology Group (JCOG0802)[1] and Altorki et al.[2] (Alliance/CALGB140503) demonstrated the benefits of sublobar resections compared to lobectomy, suggesting that the segmentectomy procedure particularly may become the standard surgical procedure in terms of overall survival rate in patients with clinical Stage 1A lung cancer. Therefore, thoracic surgeons are increasingly interested in minimally invasive segmentectomy procedures. However, segmentectomy is a more complex surgical procedure than standard lobectomy due to its anatomical complexity and variations at segmental levels, including the bronchovascular structures.[3] Gossot et al.[4] reported that to overcome the complexity of video-assisted thoracoscopic surgery (VATS) segmentectomy, the surgeon would not only need to master the techniques, but would also need to rely on various technologies such as preoperative three-dimensional (3D) modeling and/or 3D printing.[4]

Preoperative 3D modeling and 3D printing are also widely used in other surgical specialties (interventional neuroradiology, otorhinolaryngology, orthopedics, etc.).[5,6] Preoperative 3D modeling technology plays a critical role in lung resection, particularly in segmentectomy. As there are many variations in the pulmonary arteries and veins, a detailed preoperative understanding of the patient's specific anatomy can contribute to safe pulmonary surgery and prevent complications.[3] Many software programs have been developed for 3D modeling. The goal of all software is to preoperatively visualize the anatomical structures of the lung for surgeons using two-dimensional (2D) computed tomography (CT) images to improve the safety and accuracy of VATS segmentectomy.[7,8] Nevertheless, professional skill requirements and high time consumption hinder the widespread use of these systems in clinical practice.[9] AI-based software automatically learns from raw data and rapidly completes the 3D model to improve the clinical efficiency.[10] Unfortunately, owing to the high cost of AI-based software in Türkiye, open-source free software continues to be used to perform segmentectomy as intended. In the present study, we aimed to evaluate the feasibility of 3D modeling using open-source free software for preoperative planning and intraoperative guidance in uniportal VATS segmentectomy, a complex procedure.

PATIENTS AND METHODS

This single-center, retrospective study was conducted at Ondokuz Mayıs University Faculty of Medicine, Department of Thoracic Surgery between October 2020 and November 2023. A total of 196 consecutive patients who underwent anatomical lung resection using uniportal VATS were screened. Among them, 50 patients (27 males, 23 females; mean age: 60±11.1 years; range, 34 to 78 years) who underwent uniportal VATS segmentectomy were included in the study. All segmentectomies were performed by a surgeon with experience in more than 300 cases of pulmonary anatomical resection. Inclusion criteria were as follows: patients with peripheral nodules less than 2 cm in size, no calcific lymph nodes, respiratory function unsuitable for lobectomy, benign pathologies (aspergilloma, bronchiectasis, etc.), and centrally located secondary lung malignancies who underwent uniportal VATS segmentectomy. Patients who could not obtain CT of the thorax with an intravenous contrast agent due to impaired renal function were excluded from the study. A written informed consent was obtained from each patient. The study protocol was approved by the Ondokuz Mayis University Clinical Research Ethics Committee (date: 25.04.2024, no: KAEK 2024/185). The study was conducted in accordance with the principles of the Declaration of Helsinki.

The patients were divided into two groups: simple and complex segmentectomy, according to the characteristics of the surgical procedures. Group 1 (n=18): Simple segmentectomy includes right/left S6, left S1+2+3, and left S4+5 and is completed by creating only one linear intersegmental plane. Group 2 (n=32): Resections other than simple segmentectomy, which are performed by creating more than one intersegmental plane and are called complex segmentectomies.[11] The flowchart of the study is shown in Figure 1.

3D modelling and preoperative planning

All patients underwent preoperative CT imaging using a 64-detector MDCT scanner (GE Healthcare Discovery CT750 HD scanner, WI, USA), and iohexol (Opaxol, MDS Sağlık Ürünleri Tic. A.Ş., İstanbul, Türkiye) as a contrast agent (70 mL of non-ionic contrast agent (350 mg I/ML) was injected into the antecubital vein at 2 mL/s via a power injector). Digital imaging and communications in medicine (DiCOM)

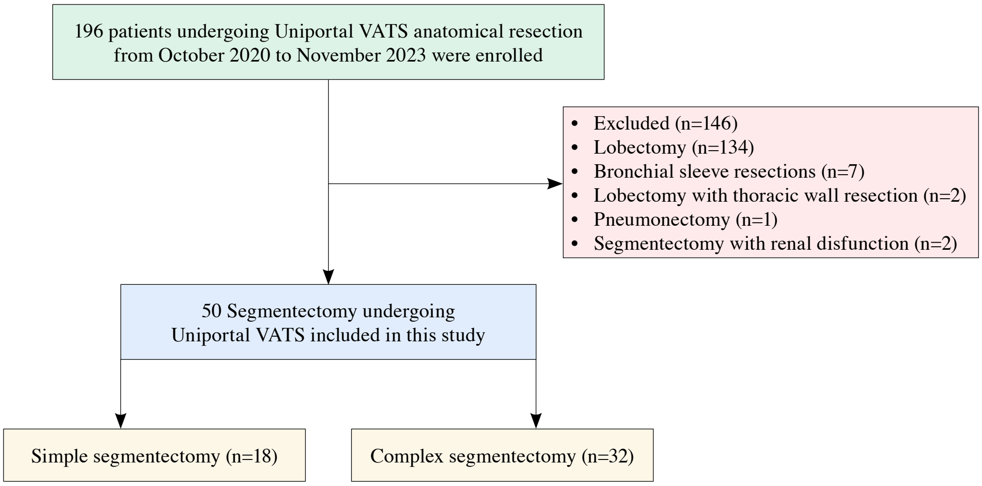

Figure 1. Study flowchart.

VATS: Video-assisted thoracoscopic surgery.

data were transferred to a dedicated workstation. Based on the contrast-enhanced CT images, 3D modelling was performed with a software-based evaluation using the software tools "Segment Editor" and "Segmentation" of the open-source 3D Slicer software (v. 5.1.1, https://www.slicer.org). For optimal results, contrast-enhanced CT images with a slice thickness of ≤1.25 mm were used for 3D modelling. Lung reconstruction was performed by identifying and segmenting the pulmonary bronchovascular structures and placing the tumor. The use of contrast medium combined with accurate contrast timing allows the system to automatically perform 3D modelling of pulmonary arteries and veins. In addition, segment extraction was performed using virtual simulation to visualize the resection site and extent of the surgical margin. The 3D reconstruction and virtual simulation of the resection for each patient were recorded in an interactive video file in which all pulmonary structures could be individually selected. The files were transferred to a mobile device. All reconstructions were performed by an operating surgeon. The patients were evaluated and approved by two independent radiologists.

Surgical technique

The patient was placed in the lateral decubitus position with the intact side facing down. A double-lumen intubation tube was placed, and general anesthesia with one-lung ventilation was performed. For uniportal surgery, a single 3 to 4-cm long incision was made in the fifth or sixth intercostal space between the anterior and mid-axillary line, as described in our previous study.[12] The incision was closed by using a silicone wound protector. A 10-mm 30° thoracoscope (HOPKINS® Forward-Oblique 30° Telescope, Karl Storz, Tuttlingen, Germany) was used as the camera, and an endoscopic sealer/separator (LigaSure™ Maryland, MN, USA) was used as an energy device

Table 1. Distribution of segmentectomies

Side	Lobe	Segment	n	%
Right	Upper	S1	10	20
		S2	4	8
		S3	2	4
		S2+S3a	1	2
	Lower	S6	5	10
		S7	2	4
		S7+8	1	2
		S6+10	1	2
		S9+10	3	6
Left	Upper	S1+2	4	8
		S1+2+3	3	6
		S3	1	2
		S3+4+5	1	2
		S4+5	4	8
	Lower	S6	6	12
		S10	1	2
		S8+9+10	1	2
Total			50	100

for tissue dissection. An endovision system integrated with an infrared light source (IMAGE1 STM Rubina® NIR/ICG, Karl Storz, Tuttlingen, Germany) was used to determine the intersegmental planes in cases with intravenous indocyanine green (ICG). The preferred surgical instruments for vascular and bronchial dissection were the node grasper (snake), dissector clamp, endovascular clamp, right clamp, and aspirator.

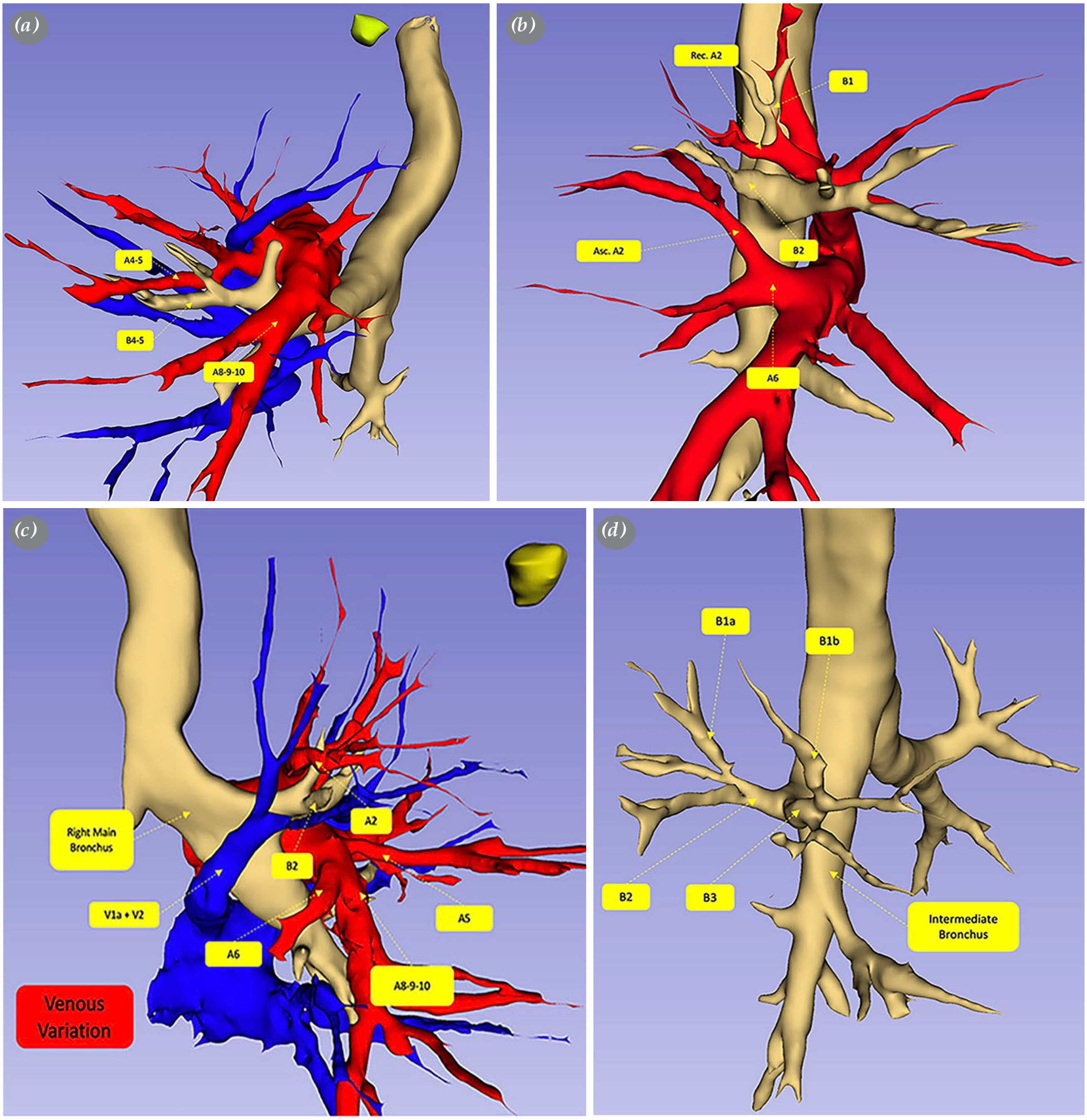

Figure 2. (a) In the patient who was scheduled for left upper lobe tri-segmentectomy (simple), the A4-5 artery is presented to proceed from the main pulmonary artery to the lingula segment together with the A3 artery from the in front of the upper lobe bronchus. **(b)** Ascending A2 artery was shown to originate from A6 in a patient with a right upper lobe S2 segmentectomy (complex) plan. **(c)** For right upper lobe S2 segmentectomy (complex), the V2 venous branch was shown to drain into the left atrium from behind the right main bronchus. **(d)** For right S1 segmentectomy (complex), B1a and B1b bronchial branches were shown to originate from B2 and B3 branches separately.

In all the patients, the pulmonary hilum was released to provide more space for lung manipulation. The 3D model of the patient on the mobile device was compared intraoperatively with the patient's anatomical structures. Vascular structures of the targeted segment were dissected, ligated with an endostapler or hem-o-lock, and divided. Segmental bronchial division was performed using an endostapler. After bronchial separation, segmentectomy was completed by insufflation-deflation of the lung or the intravenous ICG method, and the fissure and intersegmental margins were separated with an endostapler.

Statistical analysis

Statistical analysis was performed using the IBM SPSS version 26.0 software (IBM Corp., Armonk, NY, USA). Continuous data were presented in mean ± standard deviation (SD) or median (min-max), while categorical data were presented in number and frequency. Compliance with normal distribution was analyzed using the Shapiro-Wilk test. An independent two-sample t-test was used to compare normally distributed surgical times between groups. The Pearson correlation coefficient was used to examine the relationship between normally distributed data and Spearman rho correlation coefficient was used to examine the relationship between non-normally distributed data. The Wilcoxon test was used to compare the success rates of the non-normally distributed 3D models. A p value of <0.05 was considered statistically significant.

RESULTS

Uniportal VATS segmentectomy was successfully performed in 50 patients. Segmentectomies were

Table 2. Distribution of variables according to groups

	Group 1 (n=18)					Group 2 (n=32)					
	n	%	Mean±SD	Median	Min-Max	n	%	Mean±SD	Median	Min-Max	*p*
Age (year)			60.8±12.8		31-78			56.8±13.0		16-75	0.606
Sex											0.053
Male	13	72.2				14	43.8				
Female	5	27.8				18	56.3				
Side											0.001
Right	5	27.8				24	75.0				
Left	13	72.2				8	25.0				
Lobe											0.022
Upper	7	38.9				23	71.9				
Lower	11	61.1				9	28.1				
Bronchovascular variation											0.006
No	16	88.9				16	50				
Yes	2	11.1				16	50				
Variation type											0.059
Arterial	2	100				5	31.2				
Venous	0	0				7	43.8				
Bronchial	0	0				1	6.2				
Mix	0	0				3	18.8				
Success of 3D model											1.000
Bronchovascular		99.07					99.38				
Arterial		98.15					100				
Venous		100					98.44				
Bronchial		100					100				
Cause of resection											0.407
Primary cancer	15	83.3				21	65.6				
Secondary cancer	1	5.6				4	12.5				
Benign	2	11.1				7	21.9				
Complication											0.479
Intraoperative	2	11.1				1	3.1				
Postoperative	1	5.6				4	12.5				
Chest tube removal (day)				1.5	1-5				1	1-9	0.794
Postoperative hospital (day)				3	2-10				3	2-12	0.907

SD: Standard deviation.

performed in 34% (n=17) of the right upper lobe, 24% (n=12) of the right lower lobe, 26% (n=13) of the left upper lobe, and 16% (n=8) of the left lower lobe. The resected segments and their distribution according to the lobes are presented in Table 1. The overall matching success rate of the 3D model with the bronchovascular structures identified intraoperatively was 99.27%. The arterial, venous, and bronchial matching success rates were similarly high (99.33%, 99% and 100%, respectively). Anatomical variations in the bronchovascular structures of the resected segments were evaluated. The overall variation rate was 36% (n=18) among all patients. Examples of the detected variations are shown in Figure 2.

The patients were divided into two groups according to the type of segmentectomy performed: simple (Group 1) and complex segmentectomy (Group 2). There were no statistically significant differences between the two groups in terms of age and sex. The most common reason for resection in both the groups was primary lung cancer. Simple segmentectomies were performed in the left lung and lower lobes and complex segmentectomies were performed in the right lung and upper lobes (p=0.001; p=0.022). There was a significant difference between the two groups in terms of bronchovascular variation. The rate of bronchovascular variation was 11.1% (n=2) in Group 1 and 50% (n=16) in Group 2 (p=0.006). The success of preoperative 3D model matching with intraoperative bronchovascular structures did not differ between groups (Group 1/Group 2; 99.07%, 99.38%). Intraoperative complications (Group 1/Group 2; 11.1%, 3.1%) and postoperative complications (Group 1/Group 2; 5.6%/12.5%) did not significantly differ between the groups. There was no statistically significant difference in the median duration of chest tube removal (Group 1/Group 2; 1.5 /1 day) or median duration of hospital stay (Group 1/Group 2; 3 /3 days). The distribution of the groups is shown in Table 2.

DISCUSSION

In this study, we report the effects of 3D modeling on preoperative planning and intraoperative guidance in uniportal VATS segmentectomy. The 3D modeling of all patients was performed using conventional multi-slice CT images and open-source software. The 3D models were uploaded to mobile devices for intraoperative visualization. The videos uploaded to the mobile device allowed the surgeon to examine the vascularization and bronchial tree in the operating room. Intraoperative dissection and visualization matched the 3D model 99.27% of the time. There was no significant difference between simple and complex segmentectomies in terms of the 3D model matching characteristics. However, there was a significant difference between the two groups in terms of the anatomical bronchovascular structures. Variations were detected in the bronchovascular structures of 50% of the patients undergoing complex segmentectomy. There was no mortality in our study, with an intraoperative complication rate of 6% and postoperative complication rate of 10%.

There were more variations in the anatomy of the lung, particularly in the segmental anatomy, than in the lobar anatomy. These variations greatly increase the risk of vascular injury during segmentectomy, and high blood flow and velocity in the pulmonary circulation can cause high volumes of hemorrhage within a short time after injury.[13] Furthermore, in segmentectomy, which is a parenchyma-sparing surgery, only the bronchovascular structures of the target segment should be divided to minimize the functional capacity of the remaining lung segments. This requires that patient-specific segmental anatomy be precisely delineated with 3D modeling in the preoperative period. Whether segmentectomy performed with preoperative 3D modeling is superior to non-3D procedures has not yet been included in the guidelines.[14] Large-series studies on this subject are required. Fan et al.[13] argued that 3D modeling was an excellent technology for the assessment of pulmonary bronchovascular anatomy in their study. The open-source 3D Slicer software that we used in our study does not depend on a platform and can be installed on a portable laptop computer. As the software does not require expertise in computer technologies, it can be used by thoracic surgeons with radiologic competence. The model, created from thin-section CT images with a maximum thickness of 1.25 mm, allows detailed examination of the bronchovascular structures. The model is converted to a video format for review on a mobile device, and can be compared with structures in living tissues during the operation. It can also provide an idea of the amount of tissue to be removed by identifying target segment boundaries with anatomical landmarks. The widespread use of this technology would have a positive impact on the learning curve for segmentectomy surgery. In the literature, studies suggest that preoperative 3D modeling for the evaluation of bronchovascular variations may improve surgical accuracy and safety.[15,16] However, Wu et al.[17] suggested that preoperative 3D lung simulation could reduce operation time and ensure proper segmental margins and lymph node dissection. In our study, in which we used preoperative 3D modeling for anatomical segmentectomy, we compared the preoperative 3D lung model with intraoperative anatomical structures and found a high matching rate.

Segmentectomy is divided into simple and complex segmentectomies according to the surgical procedures and intersegmental planes.[11] Simple segmentectomy includes the right S6, left S6, left S1+2+3, and left S4+5 and is completed by creating only one linear intersegmental plane. Other segmentectomies, which are completed by creating more than one intersegmental plane, are classified as complex segmentectomies.[18] Wang et al.[19] reported that routine preoperative high-resolution CT (HRCT) images would be sufficient for simple segmentectomy, but emphasized the importance of preoperative 3D simulation technology for complex segmentectomy. In our study, the overall rate of bronchovascular variations was 36%. We observed a bronchovascular variation rate of 11.1% in simple segmentectomies and 50% in complex segmentectomies. Similar to the literature, a significant difference was found between simple and complex segmentectomies in terms of bronchovascular variation. This result emphasizes the importance of 3D modeling, particularly for patients scheduled for complex segmentectomy.

The complexity of the segmental anatomy of the lung and narrowing of the distal diameter of the bronchovascular structures are factors that facilitate damage to these structures during dissection. However, preoperative 3D modeling of the lung virtually reveals the direction of extension of the bronchovascular structures and their relationship with the surrounding tissues. Studies have shown that preoperative 3D modeling of the lung reduces intra- and postoperative complication rates.[20,21] In a comprehensive systematic review, Xiang et al.[22] showed that segmentectomy performed with preoperative 3D modeling could achieve better intraoperative and postoperative outcomes in terms of operative time, conversion rate, postoperative hospital stay and complications. Hu et al.[23] argued that preoperative 3D modeling had no effect on postoperative outcomes, although it had a positive effect on intraoperative complications. By contrast, Xu et al.[24] in their study comparing groups with and without 3D modeling, postoperative drainage times were significantly better in the group using 3D modeling. In this study, minor intraoperative bleeding occurred in two cases of simple segmentectomy, and bronchial injury occurred in one case of complex segmentectomy. None of the patients were converted to open thoracotomy or extended resection due to major complications. We believe that this result may be directly related to the reduced risk of intraoperative complications with 3D modeling.

Nonetheless, the present study has certain limitations. First, the sample size was not sufficiently large, and the study was designed retrospectively. A prospective study with a large case series is required for more efficient analysis. Second, the generalizability is limited due to the single-center design of the study. Third, it shows the intraoperative effects of 3D modeling and the early postoperative results. A large case series is needed to compare long-term results. Fourth, we considered the fact that intersegmental planes were not determined by the same method in all patients as a limitation. Although the main vascular structures of the target segment were compared with the 3D model, the distal borders, which play an important role in determining the segment boundaries, could not be evaluated using the standard method in all patients.

In conclusion, 3D modeling with open-source free software for preoperative planning and intraoperative guidance is a safe method for detecting bronchovascular structures in the target segment with high accuracy in uniportal video-assisted thoracoscopic surgery segmentectomy procedures. Complex procedures, such as segmentectomy, can be performed with low complication rates. We also expect that this method may have a positive impact on the learning curve of the surgeon performing the procedure. Therefore, we believe that this would be useful for all simple and complex segmentectomies.

Acknowledgments: We would like to thank radiologists Aslı Tanrivermis Sayit, MD., and Hasan Gundogdu, MD., for checking the reliability of the computed tomography images when they were reconstructed into 3D images.

Data Sharing Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions: Idea/concept, design, writing the article, analysis and/or interpretation: S.G., A.Ş.; Control/supervision, literature review, critical review: A.Ş.; Data collection and/or processing, references and fundings: S.G.;

Conflict of Interest: The authors declared no conflicts of interest with respect to the authorship and/or publication of this article.

Funding: The authors received no financial support for the research and/or authorship of this article.

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