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ORIGINAL ARTICLE

High-quality 3-dimensional image simulation for pulmonary lobectomy and segmentectomy: results of preoperative assessment of pulmonary vessels and short-term surgical outcomes in consecutive patients undergoing video-assisted thoracic surgery[†]

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Abstract

OBJECTIVES: The aim of this study was to evaluate the effectiveness of 3-dimensional computed tomography (3D-CT) software in short-term surgical outcomes and the assessment of variations of pulmonary vessel branching patterns on performing video-assisted thoracic surgery (VATS).

METHODS: The study included 179 consecutive patients who had undergone VATS anatomical lung resection, of which 172 were lobectomies (96%) and 7 were segmentectomies (4%), from May 2011 through January 2013. There were 124 patients (69%) in whom 3D-CT was performed and 55 patients (31%) who had not undergone 3D-CT. Observed actual pulmonary vessel branching patterns by intraoperative findings or footage were compared with the 3D image findings. Various surgical outcomes, including the occurrence of postoperative complications, in this study defined as those of Grade 2 or above under the Clavien–Dindo classification system, and total operative time, were retrieved from available clinical records.

RESULTS: Among the 124 patients with preoperative 3D imaging, there were 5 (4%) conversions from VATS to thoracotomy. The incidence rate of patients with postoperative complications was 8% ($n = 10$), and there were no 30-day or 90-day mortalities. Pulmonary artery (PA) branches were precisely identified for 97.8% (309 of 316) of branches on 3D images, and the sizes of the seven undetected branches (five in the right upper lobe, two in the left upper lobe) ranged from 1 to 2 mm. The 3D images accurately revealed 15 cases (12%) of anomalous or unusual PA branches and 5 cases (4%) of variant pulmonary veins. Multivariate logistic regression analysis of the association with postoperative complications and operative time in 165 lung cancer patients demonstrated that male gender was the only statistically significant independent predictor of complications (risk ratio: 5.432, $P = 0.013$), and patients without 3D imaging tended to have operative complications (risk ratio: 2.852, $P = 0.074$), whereas conducting the 3D-CT (risk ratio: 2.282, $P = 0.021$) as well as intraoperative bleeding amount (risk ratio: 1.005, $P = 0.005$) had significant association with operative time.

CONCLUSIONS: High-quality 3D-CT images clearly revealed the anatomies of pulmonary vessels, which could play important roles in safe and efficient VATS anatomical resection.

Keywords: 3-Dimensional computed tomography • Simulation • Video-assisted thoracic surgery • Lobectomy • Pulmonary vessels

INTRODUCTION

Video-assisted thoracic surgery (VATS) lobectomy and segmentectomy have been established as standard surgical techniques for the treatment of lung cancer, metastatic lung tumours and benign lung tumours. A number of reports have documented the safety and effectiveness of a thoracoscopic approach, which has less morbidity, better postoperative respiratory function and equivalent oncological outcomes to conventional thoracotomy [1–4]. Anatomical variants of pulmonary vessels can cause serious problems such as unexpected bleeding in patients undergoing VATS [5, 6]. Detailed preoperative understanding and simulations of the surgical anatomy using image modalities would greatly contribute to safely performing VATS.

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Multidetector computed tomography (MDCT) allows surgeons to construct 3-dimensional (3D) images of lung structures. We have used 3D lung modelling based on CT images taken using the Fujifilm Synapse Vincent system (Fujifilm Corporation, Tokyo, Japan) to obtain 3D images of the pulmonary vessels and the tracheobronchial tree for surgical simulations [7, 8]. Several reports have addressed the usefulness of pre- or intraoperative use of 3D evaluations in the field of thoracic surgery [7–12]. However, the influence of 3D simulation on perioperative surgical outcomes in VATS has not been well described. The aim of this study was to evaluate the effectiveness of 3D software in short-term surgical outcomes and the preoperative assessment of variations of pulmonary vessel branching patterns for safely performing VATS.

PATIENTS AND METHODS

Patients

From May 2011 to January 2013, 561 patients underwent pulmonary resection at our department. Among them, 179 (31.9%) consecutive patients who had undergone VATS anatomical lung resections were included in this retrospective study. Our original indications of VATS anatomical resection for malignancies were for peripheral tumours less than 5 cm in diameter without nodal involvement. However, we have applied the VATS procedure in patients with multiple comorbidities who would otherwise not be suitable candidates for the conventional thoracotomy approach. We have preoperatively constructed 3D lung modelling based on CT images of lung structures taken using the Synapse Vincent system for the majority of patients scheduled for VATS lobectomy or segmentectomy. Data collection and analyses were approved and the need to obtain written informed consent from each patient was waived by the Institutional Review Board of Tokyo Medical University.

Preoperative 3D image construction and simulation

Patients underwent CT imaging with a 64-channel MDCT (Light Speed VCT, GE Medical Systems, Milwaukee, WI, USA) set at the following parameters: gantry rotation speed of 0.4 s per rotation, collimation of 0.625 mm, table incrementation speed of 39.37 mm/s with a helical pitch of 0.984, tube voltage of 120 kV, and the tube current was used with an automatic exposure control system. Axial sections (1.25 mm in thickness) were reconstructed at intervals of 1.0 mm. A total of 100 ml of iohexol (Omnipaque, 300 mg of iodine per ml; Daiichi-Sankyo Pharmaceutical, Tokyo, Japan) was injected by a mechanical injector (Dual Shot GX7; Nemoto Kyorindo, Tokyo, Japan) at a rate of 1.5–2.0 ml/s without an injection of saline solution afterwards. Each CT image was acquired within 1 breath hold of about 5 s, after a delay of 70 s during which the contrast media injection took effect. The presented CT scan protocol has been used for not only the 3D image construction but also standard staging for lung cancer patients to be suitable for contrast radiography. These digital imaging and communication in medicine data were transferred to a workstation with the volume-rendering reconstruction software. After this step, a surgeon can construct 3D images completed within approximately 5 min for surgical simulations. We have performed VATS with double monitor guidance: one was a thoracoscopy television monitor, and the other was the 3D imaging system. The simulation system was implemented as a plug-in in the processing workstation (Dell Precision T5500, Windows 7 Professional, 64-bit, 12 GB, DDR3 RDIMM).

Operative procedure

Operations were performed with the patient in the lateral decubitus position under general anaesthesia with one-lung ventilation. Three or four incisions were used in each patient. A 10-mm camera port was placed in the sixth intercostal space (ICS) at the midaxillary line, through which a 30-degree thoracoscope was positioned. An access incision of 3 cm was placed in the fourth ICS and centred at the anterior axillary line, and a 10-mm accessory port was placed in the sixth ICS at the anterior axillary line. A 15-mm assist port was placed at the tip of the scapula. Rib resection or rib spreading was not performed.

Analysing evaluation data

To determine the ability of 3D images to enable the assessment of pulmonary artery (PA) branching patterns involved in operation, vascular size, the route of the pulmonary vein (PV) and the results of all examinations were interpreted by two surgeons (at least one of whom was a board-certified thoracic surgeon) and one chest radiologist (Soichi Akata) in consensus. The intraoperative footage was postoperatively evaluated by two surgeons, who were blinded to patient identification. When pulmonary vessels identified by the footage could not be visualized in the 3D images, they were considered ‘undetected’ vessel branches. Short-term outcomes, such as operating time, approximate blood loss, mortality rate and postoperative complications, were retrieved from available clinical records. The development of postoperative complications in this study was defined as Grade 2 or above for severe complications under the Clavien–Dindo classification system.

Statistical analysis

The χ^2 test and Fisher's exact or Student's *t*-test were used to compare proportions and continuous variables in analysing the frequency of occurrence of postoperative complications and operative time. Multivariate analyses were performed using the multiple logistic regression analysis, and we checked the validity of the model using the Hosmer–Lemeshow χ^2 test (a larger *P* value signifies greater reliability) on an external validation data set. All tests were two-sided, and *P*-values less than 0.05 were considered to indicate a statistically significant difference between the two groups. All statistical calculations were performed using the SPSS statistical software package (version 21.0; DDR3 RDIMM, SPSS, Inc., Chicago, IL, USA).

RESULTS

The characteristics of the patients who underwent VATS anatomical lung resection during this study period are summarized in Table 1. The study cohort of 179 patients included 88 men and 91 women, of whom 165 (92%) had primary lung cancer and 172

Table 1: Patients who underwent VATS anatomical resection during this study period (*n* = 179)

Variables	No. of patients (%)
Age, median (years, range)	68 (26–87)
Sex	
Men	88 (49)
Women	91 (51)
Diagnosis	
Lung cancer	165 (92)
Metastatic lung tumour	6 (3)
Benign lung disease	8 (5)
Type of surgery	
Lobectomy	172 (96)
Right upper lobectomy	54
Right middle lobectomy	17
Right lower lobectomy	41
Right middle and lower lobectomy	2
Left upper lobectomy	37
Left lower lobectomy	21
Segmentectomy	7 (4)
Left S1+2–3	3
Right S3	1
Right S6	1
Left S4 + 5	1
Left S8–10	1
Preoperative 3D imaging	
Present	124 (69)
Absent	55 (31)

(96%) underwent lobectomy. This study involved 124 patients (69%) in whom 3D imaging was performed preoperatively and 55 patients (31%) in whom 3D imaging was not available because of contraindication to the use of contrast radiography (e.g., allergies to contrast medium, severe diabetes or bronchial asthma) or patient refusal against repeated imaging studies.

The characteristics and surgical outcomes of 124 patients undergoing 3D imaging are given in Table 2. There were 5 (4%) conversions from VATS to thoracotomy because of vessel bleedings. The frequency of patients presenting with complications with Grade 2 or above was 8% (*n* = 10), and there were no 30-day or 90-day operative mortalities.

According to intraoperative findings, PA branches were precisely identified on the basis of preoperative 3D-CT imaging (Table 3) in 97.8% (309 of 316) of vessels and 94.4% (117 of 124) of patients. There were 7 patients with undetected PA branches including 5 right upper lobectomies (RULs) and 2 left upper lobectomies (LULs). Undetected PA branches were the truncus arteriosus superior in 3 patients, the ascending artery in 2 patients, and the apical artery and lingular artery in 1 patient each. A representative image of an undetected ascending artery is shown in Fig. 1. The actual sizes of the 7 missed branches in the 7 patients were all less than 2 mm. The 3D image findings in PA branches were identical to operative findings in cases other than upper lobectomy. The number of patients with anomalous or uncommon PA branching patterns was 15 (12%). A summary of the 3D image findings in patients with anatomical variants of the PA is given in Supplementary material, Table S1. All anomalous or uncommon PA branches were accurately confirmed by 3D imaging. Of the 26 patients receiving LUL, 5 patients (19%) had anatomical variants of mediastinal lingular branches of the PA, which included the A4 + A5 type and either the A4 or A5 type. In addition, there were 5 patients with lingular PA arising from the basilar artery, 2 patients with 2

Table 2: Patients who underwent VATS anatomical resection with the preoperative 3D imaging (*n* = 124)

Variables	No. of patients (%)
Age, median (years, range)	68 (35–87)
Sex	
Men	60 (48)
Women	64 (52)
Diagnosis	
Lung cancer	115 (93)
Metastatic lung tumour	5 (4)
Benign lung disease	4 (3)
Type of surgery	
Lobectomy	119 (96)
Right upper lobectomy	38
Right middle lobectomy	13
Right lower lobectomy	27
Right middle and lower lobectomy	1
Left upper lobectomy	26
Left lower lobectomy	14
Segmentectomy	5 (4)
Left S1 + 2–3	2
Right S6	1
Left S4 + 5	1
Left S8–10	1
Conversion from VATS to thoracotomy	5 (4)
Operative time, mean (min, range)	230 (132–444)
Bleeding, mean (ml, range)	110 (0–1406)
Postoperative complications (Grade ≥ 2)	
Present	10 (8)
Arrhythmia	3
Prolonged air leakage	2
Chylothorax	1
Bacterial pneumonia	1
Bleeding	1
Empyema	1
Recurrent nerve paralysis	1
Absent	114 (92)
30-day mortality	0
90-day mortality	0

superior segmental arteries coming directly from the main PA, 2 patients with double ascending arteries, 1 patient without an ascending artery and 1 patient with triple middle lobe branches (Fig. 2). The 3D imaging showed 5 patients with anomalous PVs (Supplementary material, Table S2).

We evaluated the relationship between various clinical factors and the occurrence of postoperative complications (Table 4) or overall operative time (Table 5) in 165 patients with primary lung cancer. Sex ($P = 0.002$), pulmonary function test of forced expiratory volume in 1 s % (FEV1.0%; $P = 0.011$), and the presence or absence of respiratory comorbidities including chronic obstructive pulmonary disease, interstitial pneumonia, bronchial asthma etc. ($P = 0.018$) were found to be associated with the occurrence of complications. Conducting the preoperative 3D imaging tended to have associations, but the difference was not statistically significant ($P = 0.054$). On multivariate logistic regression analysis for these statistically or marginally significant factors, male gender was shown to be the only statistically significant independent predictor (risk ratio: 5.432, $P = 0.013$, Hosmer–Lemeshow χ^2 test = 0.89, $P = 0.641$), and 3D imaging also tended to be associated with the occurrence of complications (risk ratio: 2.852, $P = 0.074$).

There were significant associations between total operative time (dichotomized at mean operative time, 237 min) and conducting

Table 3: Identification rate of the 3D imaging in pulmonary artery branches according to type of surgery

Variables	No. of patients (%)	No. of PABs involved in resection		Identification rate (%)		Undetected PABs (no. of patients)
		3D images	Surgical findings	A per-vessel basis	A per-patient basis	
Overall	124 (100)	309	316	97.8	94.4	1 mm (1)/2 mm (6)
Type of surgery						
Right upper lobectomy	38 (31)	84	89	94.4	86.8	1 mm (1)/2 mm (4)
Right middle lobectomy	13 (10)	24	24	100	100	–
Right lower lobectomy	27 (22)	55	55	100	100	–
Right middle and lower lobectomy	1 (1)	2	2	100	100	–
Left upper lobectomy	26 (21)	99	101	98.0	92.3	2 mm (2)
Left lower lobectomy	14 (11)	33	33	100	100	–
Segmentectomy	5 (4)	12	12	100	100	–
Uncommon PAB pattern	15 (12)	50	50	100	100	–

PABs: pulmonary artery branches.

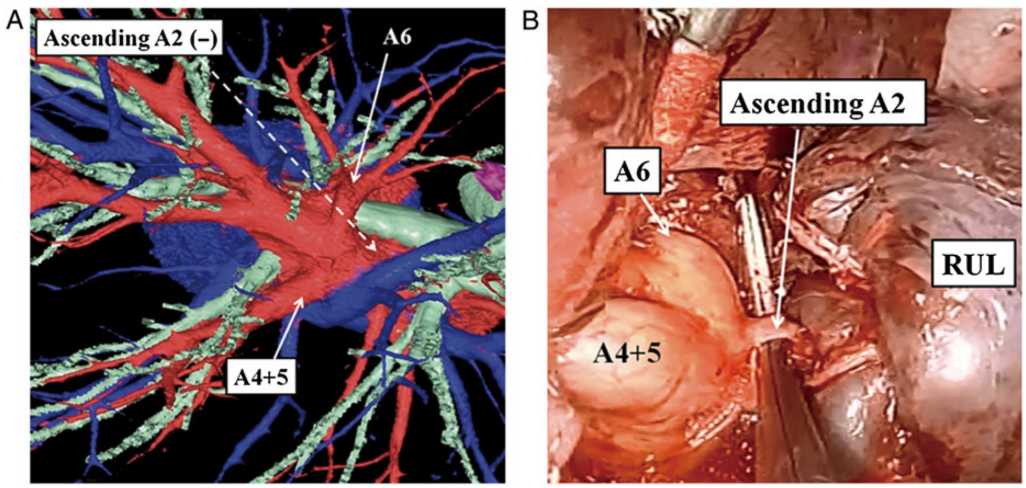

Figure 1: (**A**) A 3-dimensional computed tomographic image of the right pulmonary vessels. In this patient, a right upper lobectomy was performed. An ascending artery was not detected. (**B**) The intraoperative findings in this patient demonstrated the 2-mm ascending artery branches from the pulmonary artery.

the 3D imaging (risk ratio: 2.282, $P = 0.021$) and intraoperative blood loss (risk ratio: 1.005, $P = 0.005$) on univariate and multivariate analysis (Hosmer–Lemeshow χ^2 test = 5.92, $P = 0.656$).

DISCUSSION

We set out to identify the effectiveness of 3D-CT imaging for preoperative assessment of the branching patterns of pulmonary vessels and short-term surgical outcomes. A total of 97.8% of PA branches were precisely identified and all anomalous or uncommon PA and PV branching patterns were accurately confirmed by 3D imaging. In addition, patients undergoing preoperative 3D imaging tended to have lower incidences of postoperative complications and have significantly shorter operative time than those without the 3D simulations.

In reports in the literature concerning patients undergoing thoracoscopic and open surgery, 95–98% of PA branches were preoperatively identified using 3D-CT angiography, similar to our results [10–12]. Several authors also studied anomalous PA, PV or bronchial variations for surgery using 3D reconstruction [9, 12–15]. 3D simulation is considered to be useful in performing anatomical segmentectomy for small lung tumours for identifying the intersegmental veins as boundary lines of the pulmonary segments in order to determine the surgical margins using lateral 3D images and to identify the target segmental bronchi using vertical 3D images before segmentectomy [8, 16, 17]. These reports show that intraoperative visual guidance of the target pulmonary vessels and bronchi, and their relationship to one another as revealed by high-quality 3D images, could help thoracic surgeons perform safer anatomical lung resection and be prepared for more complicated operations.

In our clinical experience with using the Synapse Vincent software, there have been advantages of the 3D system that are based on volume-rendering techniques. First, a surgeon without expert knowledge concerning synthetic imaging can quickly and easily construct 3D images of each patient. The mean processing time required to construct a 3D angiographic image is approximately 5 min. The 3D imaging also allows us to freely rotate the objects and change the dimensions of images. The virtual 3D-CT can provide an overview of the 3D relationships of the pulmonary vessel pathways and the tracheobronchial tree. Thus, it is employed for preoperative simulations, which also help educate trainees about surgical anatomy. Secondly, unlike the currently

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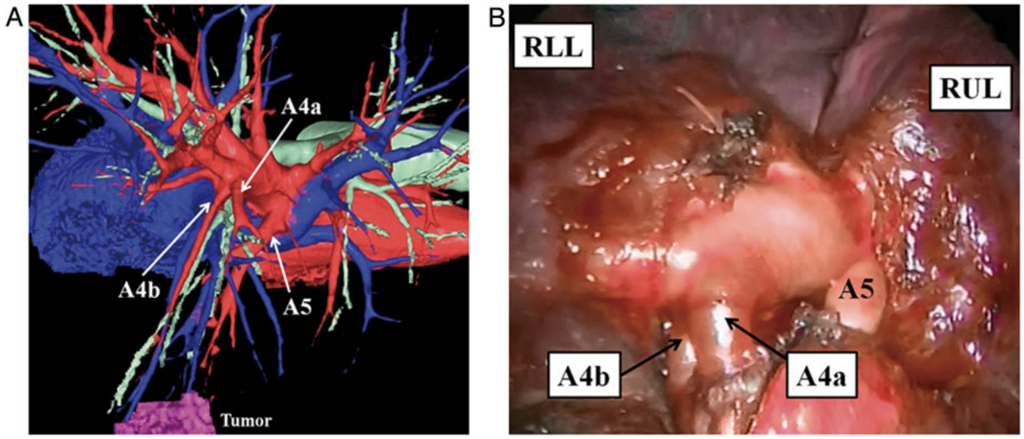

Figure 2: (**A**) The 3-dimensional computed tomographic image of the right pulmonary vessels showed that this patient had triple middle lobe pulmonary artery branches. (**B**) The intraoperative findings of this patient showed triple middle pulmonary artery branches corresponding to the 3-dimensional computed tomographic image.

Table 4: Association between clinical factors and the development of postoperative complications in patients who underwent VATS anatomical resection with primary lung cancer (*n* = 165)

Variables	Postoperative complications		Univariate analysis	Multivariate analysis		
	Present	Absent	*P*-value	RR	95% CI	*P*-value
Overall	18	147				
Sex						
Men	15	65		5.432		
Women	3	82	0.002	1	1.427–20.683	0.013
Age, median (years, range)	69 (27–87)		0.46			
Clinical staging						
IA	11	104				
IB	5	28				
IIA	1	7				
IIB	1	3				
IIIA	0	4				
IIIB	0	1	0.81			
Tumour location						
Right upper lobe	4	47				
Right middle lobe	2	14				
Right lower lobe	4	35				
Left upper lobe	6	34				
Left lower lobe	2	17	0.87			
Preoperative 3D imaging						
Present	9	106		1		
Absent	9	41	0.054	2.852	0.904–8.999	0.074
FEV1.0%, median (%, range)	74 (44–89)		0.011	0.962	0.891–1.039	0.861
Operative procedure						
Lobectomy	18	143				
Segmentectomy	0	4	0.48			
Conversion from VATS to thoracotomy						
Present	0	6				
Absent	18	141	0.38			
Intraoperative blood loss, mean (ml, range)	112 (0–1406)		0.89			
Operative time, mean (min, range)	237 (131–455)		0.65			
Respiratory comorbidity						
Present	8	29		1.153	0.233–5.716	
Absent	10	118	0.018	1		0.25
Cardiovascular comorbidity						
Present	1	10	0.51			
Absent	17	137				
Diabetes						
Present	0	7	0.34			
Absent	18	140				

RR: risk ratio; CI: confidence interval; FEV1.0: forced expiratory volume in 1 s.

Table 5: Association between clinical factors and operative time (<237 min vs ≥237 min) in patients who underwent VATS anatomical resection with primary lung cancer (n = 165)

Variables	Univariate analysis, *P*-value	Multivariate analysis		
		RR	95% CI	*P*-value
Operative time, mean (min, range)	237 (132–455)			
Sex	0.26			
Age	0.15			
Clinical staging: IA/IB/IIA/IIB/IIIA/IIIB	0.25			
Tumour laterality: right/left	0.77			
Preoperative 3D imaging: present/absent	0.019	2.282	1.131–4.604	0.021
Conversion from VATS to thoracotomy: present/absent	0.77			
FEV1.0%	0.31			
Intraoperative blood loss	0.001	1.005	1.001–1.009	0.005
Operative procedure: lobectomy/segmentectomy	0.21			
Respiratory comorbidity: present/absent	0.08			
Cardiovascular comorbidity: present/ absent	0.24			
Diabetes: present/absent	0.68			

RR: risk ratio; CI: confidence interval; FEV1.0: forced expiratory volume in 1 s.

available 3D-CT software programs, this system can show 3D images of the PA and the PV separately from the data of only one conventional CT scan. It can thereby reduce the radiation exposure dose. In contrast to the conventional method, we do not have to inject contrast media rapidly, and the infusion rate is sufficient at 1.5–2 ml/s. Consequently, we have not had any leakage accidents during contrast media infusion.

The disadvantages of 3D imaging include its potential deficiency in identifying bilateral upper lobe PA branches owing to the anatomically complex overlap of PA and PV branches. The ascending artery and truncus superior artery are often misidentified and confused with the apical segment vein or interlobar veins on 3D imaging. This might be due to the far more complicated ramification patterns of the PA in the upper lobe, particularly in the right upper lobe, than in the middle and lower lobes. However, we postulate that 3D imaging should be deemed acceptable because of the relatively low frequency of undetected PA branches.

The optimal strategy of managing postoperative complications of VATS anatomical resection is to prevent their occurrence. Perioperative complications and mortality with VATS lobectomy have been reported to occur at rates of ∼5–32% and 0–7%, respectively [2, 18–20]. In the present study, postoperative complications in patients undergoing 3D imaging occurred in 8% with no mortality, and the risk of development of any complication in patients with 3D imaging was lower in comparison to those without 3D imaging. Notably, preoperative 3D simulation as well as intraoperative bleeding amount had significant association with total operative time. Possible reasons to explain these results are the assumptions that detailed surgical simulation and shared virtual lung anatomical information provided by 3D images between operating surgeons and a thoracoscopist might improve the safe and efficient performance of VATS, without causing vascular injuries due to unusual PA branching patterns, and thereby support a calm and efficient setting during lung resection.

The frequency of conversion from VATS lobectomy to open thoracotomy has been reported to range from 2% to as high as 23% [18, 19, 21, 22]. Although the most crucial concern with unexpected conversion to open thoracotomy are the possible increases in the risk of mortality and the development of complications, no postoperative complications arose in our 5 patients undergoing the 3D-CT (date not shown). Depending on the skill and ability to predict which patients are more likely to require conversion, the occurrence of serious complications can often be avoided. 3D information will be useful in training surgeons learning VATS procedures by shared real-time imaging with an experienced surgeon, influencing a surgeon's learning curve.

The limitations of this study are its retrospective nature and potential bias. Patient selection bias in conducting the preoperative 3D imaging may influence the result of short-term benefits in adverse events and operative time. To truly show the benefits of 3D software, a prospective randomized trial is needed.

In conclusion, this study demonstrated that preoperative simulations using 3D-CT angiography for the assessment of pulmonary vessel branching patterns appear to be beneficial for the safe and efficient performance of VATS anatomical resection and for further understanding of the surgical anatomy related to general thoracic surgery. Further advances in 3D-CT imaging technology will be useful in the development of not only VATS and open thoracotomy, but also robotic surgeries and cognitive and technical surgical education systems, without exposing patients to unnecessary risks.

SUPPLEMENTARY MATERIAL

Supplementary material is available at *EJCTS* online.

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