Original Article

Evaluating three-dimensional lung reconstructions for thoracoscopic lung resections using open-source software: a pilot study

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Background: Preoperative three-dimensional (3D) lung reconstructions can reduce intraoperative blood loss, conversion rate, and operation duration. These 3D reconstructions are predominantly provided by commercial expensive products, hence we aimed to assess the usability and performance of preoperative 3D lung reconstructions created with open-source software.

Methods: Patients were invited to participate in this prospective pilot study if they were planned for uniportal video-assisted thoracoscopic surgery (VATS) lobectomy or segmentectomy between January and February 2023. Participants were excluded if a two-dimensional (2D) late-arterial-phase computed tomography (CT) scan contained motion artifacts, another surgical procedure was performed, or the surgery was canceled. After informed consent was obtained, 3D lung reconstructions were constructed using open-source 3D Slicer software. The system usability score (SUS) questionnaire assessed the usability of these reconstructions, whilst performance was evaluated based on anatomical validity compared to prior 2D CT assessment as well as operative findings. Descriptive statistics were reported.

Results: Thirteen patients were included, of whom one underwent a segmentectomy. Eighty-three percent of the 3D lung reconstructions scored above average (SUS >68). Compared to 2D CT scans, 38% of lung nodule segmental locations were detected more accurately through 3D lung reconstructions. Furthermore, 3D lung reconstructions revealed anatomical variations in 62%, which were not recognized on 2D CT scans, and provided surgeons with insights that would change the procedure and/or transection planes in 62%. One 3D lung reconstruction failed to demonstrate an intraoperative recognized segmental pulmonary artery (A6) branch.

Conclusions: Three-dimensional lung reconstructions created with open-source software were usable and effective for uniportal VATS anatomical resections.

Trial Registration: ClinicalTrials.gov/NCT06132607.

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Keywords: Video-assisted thoracoscopic surgery (VATS); lung cancer; three-dimensional reconstruction; three-dimensional simulation; open-source software

Submitted Feb 07, 2024. Accepted for publication May 19, 2024. Published online Jul 16, 2024.
doi: 10.21037/tlcr-24-134
View this article at: https://dx.doi.org/10.21037/tlcr-24-134

Introduction

Surgery is the treatment of choice for early-stage non-small cell lung cancer (1), with minimally invasive surgical techniques including video-assisted thoracoscopic surgery (VATS) and robotic-assisted thoracic surgery for anatomical lung resections as common practice (2). For patients with early-stage lung cancer, conventional treatment has been a lobectomy with systematic lymph node dissection (3). However, as evidenced by two recent high-impact randomized controlled trials, thoracoscopic segmentectomy does not result in inferior oncological outcomes when compared to thoracoscopic lobectomy in patients with early-stage lung cancer with a tumor diameter of 2 cm or less (4,5). As a result, the standard procedure is gradually changing into a parenchyma-sparing and pulmonary function-preserving segmentectomy (6). Notwithstanding, thoracoscopic segmentectomies can be a technically challenging procedure due to the complex (sub)segmental anatomy, anomalies, and the inherent difficulty of identifying the exact segmental lung nodule location (7).

Preoperative three-dimensional (3D) lung reconstructions have been recommended by the European Society of Thoracic Surgeons as a valuable asset to the surgical planning of minimally invasive anatomical pulmonary resections (8). These 3D lung reconstructions can display broncho-vascular structures and patient-specific variations within the pulmonary artery (9-11), pulmonary vein (9-11), and bronchi (11). Moreover, the segmental location of the nodule can be determined more accurately (12), which can ensure an adequate and safe resection margin (8,13). The use of 3D lung reconstructions can also reduce intraoperative blood loss, conversion rate, and operation duration (14).

Various semi-automatic software programs can be used to create 3D lung reconstructions for surgical planning, most of which are expensive commercial products (around €600 per patient). Limited research has demonstrated that open-source software such as 3D Slicer has the ability to create 3D reconstructions of the lungs, airways, pulmonary vessels, and lung nodules (15). However, the potential of these 3D lung reconstructions created with open-source 3D Slicer software has not been tested in a clinical setting yet. Hence, this prospective pilot study aimed to evaluate the usability and performance of 3D lung reconstructions developed with an in-house segmentation protocol using open-source 3D Slicer software for preoperative planning of uniportal VATS lobectomy and segmentectomy. We present this article in accordance with the CONSORT extension Pilot and Feasibility trial reporting checklist (available at https://tlcr.amegroups.com/article/view/10.21037/tlcr-24-134/rc).

Highlight box

Key findings

- In this pilot study, thirteen three-dimensional (3D) lung reconstructions were developed for 12 lobectomies and one segmentectomy. Results demonstrated that 83% of the 3D lung reconstructions were experienced to be usable for preoperative planning [system usability score (SUS) >68] and 62% revealed anatomical variations that were overlooked by the physician on (conventional) computed tomography. Transection planes and/or the surgical plan would potentially have changed in 62%.

What is known and what is new?

- Three-dimensional lung reconstructions can provide for more insights in the patient-specific pulmonary anatomy and ensure the surgical margin of segmental lung nodules during preoperative planning of segmentectomy.
- Three-dimensional lung reconstructions developed with open-source software show to be usable and effective. In addition, it can also be beneficial for minimally invasive lobectomy procedures as a surgical roadmap.

What is the implication, and what should change now?

- 3D lung reconstructions created with 3D slicer were usable and effective for uniportal video-assisted thoracoscopic surgery segmentectomy and lobectomy in a clinical setting. It may be a cost-reducing alternative compared to expensive commercial software products.

Methods

Study design and setting

We conducted a single-center single-arm prospective pilot study within our thoracic surgery department between January and February 2023. Three-dimensional lung reconstructions were created by a technical physician (I.E.W.G.L.) and a technical physician student (V.P.S.O.). Technical physicians are healthcare professionals in the Netherlands who combine knowledge of technology and medicine and are licensed to perform medical interventions. Three thoracic surgeons (with at least five years of uniportal VATS experience) and one surgical resident in thoracic surgery assessed these 3D lung reconstructions for preoperative planning of uniportal VATS anatomical resections. The primary outcome of this study, the usability of the 3D lung reconstructions, was evaluated using the postoperative system usability score (SUS) questionnaire (16,17). In addition, the performance was evaluated based on the anatomical validity of the 3D lung reconstructions compared to the two-dimensional (2D) CT scan and intraoperative findings. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Institutional Medical Ethical Review Committee of Zuyderland and Zuyd University of Applied Sciences (approval number: 20220105; approval date: December 16, 2022). This prospective pilot study was registered on ClinicalTrials.gov (approval number: NCT06132607, approval date: November 15, 2023).

Patient selection

We aimed to include at least 12 patients in our pilot study based on the sample size for pilot studies defined by Julious (18). Patients were recruited during preoperative consultation with the thoracic surgeon. All patients with suspected or biopsy-proven lung cancer who were scheduled for a uniportal VATS lobectomy (with or without wedge resection for frozen-section analysis) or segmentectomy (tumor less than 2 cm) were eligible. Patients were excluded if the preoperative computed tomography (CT) scan contained motion artifacts, the surgery was canceled, or the planned surgery was changed intraoperatively to another procedure. For each patient, written informed consent was obtained.

Image acquisition

Diagnostic late arterial phase contrast-enhanced CT scans were acquired at a fixed time of 40 seconds after intravenous administration of contrast material. Two different positron emission tomography (PET)/CT systems were used, including the Discovery MI (GE medical systems, Chicago, United States) and the GEMINI TF TOF 16 (Phillips, Eindhoven, the Netherlands). Images of the Discovery MI had a slice thickness of 0.625 mm, no gantry tilt, and a single collimation width of 0.625 mm, and were scanned in helical mode with a spiral pitch factor of 0.97. Images of the Phillips GEMINI TF TOF 16 had a slice thickness of 0.800 mm, no gantry tilt, a single collimation width of 0.800 mm, and were scanned in helical mode with a spiral pitch of 0.95. Both systems used 120 kVp, 108 mA, and a 512×512 matrix size. The used reconstruction method was filtered back projection with a standard convolutional kernel. CT scans were formatted in Digital Imaging and Communication in Medicine (DICOM) files.

In general, patients received a fixed amount of 100 mL of non-ionic iodinated contrast material (Xenetix 300, Guerbet, Villepinte, France) at a rate of 3 mL/sec, except for patients who weighed less than 53 kg (contrast volume is equal to 1.9 times their weight in kg), or patients who weighed more than 90 kg and were planned to undergo an additional CT scan of the abdomen, who received a (fixed amount of 120 mL).

Three-dimensional lung reconstruction

Prior to the pilot study, the surgeons who were involved in the study set several requirements for the 3D lung reconstructions (*Table 1*), which were implemented in the in-house 3D Slicer protocol for Microsoft Windows (v5.0.2, version 2022, Redmond, U.S., https://www.slicer.org). Our in-house developed 3D lung reconstruction protocol (*Figure 1*, step-by-step guide in Appendix 1) used several extensions of the "Segment Editor" application and the "Chest Imaging Platform" application (20,21).

Surgical technique

Each anatomical resection was performed by two dedicated thoracic surgeons, assisted by a surgical resident and operating room nurse. A dedicated team of three senior thoracic surgeons performed these procedures and has a combined experience of 3 to 5 years performing multiportal VATS lobectomy, followed by 8 years of lobectomy experience through uniportal VATS. In 2018, this team started to perform uniportal VATS segmentectomies. The

Table 1 Requirements of the 3D lung reconstructions

Item in 3D lung reconstruction	Requirement
Bronchial structures	Segment the target lobe and adjacent lobe bronchial branches
	Up to the 3rd generation† of bronchi (segmental)
	In case of a planned uniportal VATS segmentectomy, up to the level of the pulmonary nodule location
Lung nodule and resection margin	Solid and non-solid part of the tumor do not have to be segmented separately
	Safety margin of 2 cm around the lung nodule
Pulmonary arteries	Segment the target lobe and adjacent lobe's pulmonary arteries
	Show the main pulmonary artery branch up to the level of the 4th generation† of bronchi (subsegmental)
	Remove the pulmonary trunk and other heart structures
Pulmonary veins	Segment the target lobe and adjacent lobe's pulmonary veins
	Show the origin of pulmonary veins up to the 3rd generation† of bronchi (segmental)
	Remove the other heart structures
Display features	Rotatable
	Separate and simultaneous view of the anatomical structures
	Zoom function

†, classification according to Weibel's model (19). 3D, 3-dimensional; VATS, video-assisted thoracoscopic surgery.

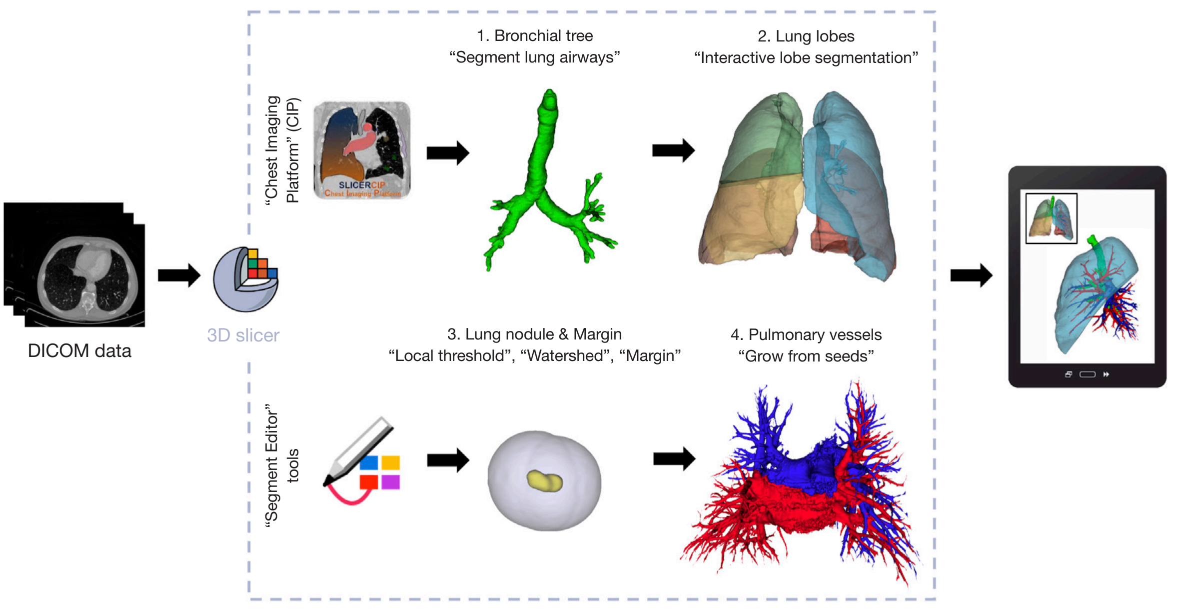

Figure 1 Overview of the 3D Slicer segmentation workflow. After the, DICOM data is imported into 3D Slicer, the bronchial tree was segmented first, followed by the lobes, both using the "Chest Imaging Platform" via the modules "Segment Lung Airways" and "Interactive Lung Segmentation", respectively. Third, the lung nodule and surgical safety margin are determined using the "Local threshold", "Watershed", and "Margin" extensions embedded in 3D Slicer. Fourth, the fast region-growing algorithm "Grow from seeds" is used to segment the pulmonary arteries and veins. Finally, any necessary manual adjustments were made and the 3D lung reconstruction was exported to a portable device. The logos of 3D Slicer and the 3D Slicer's applications "Chest Imaging Platform" and "Segment Editor" tools were copied from the 3D Slicer software program (credit: https://www.slicer.org/) or developers (credit: https://chestimagingplatform.org/). 3D, 3-dimensional; DICOM, Digital Imaging and Communication in Medicine; CIP, Chest Imaging Platform.

surgical resident was in her final year of training. All patients underwent a resection using uniportal VATS under general anesthesia and single-lung ventilation. A single 4–5 cm incision was made in the fifth intercostal space in the anterior axillary line. A 10 mm 30-degree thoracoscope was inserted. After transection of the target bronchi and pulmonary vessel branches, the target segment(s) or lobe was resected. For segmentectomies, the intersegmental planes were visualized using intravenous indocyanine green (12.5 mg) and near-infrared imaging before the transection of the parenchyma (22). A lobe-specific lymphadenectomy was performed dissecting both mediastinal and hilar lymph nodes. After surgery, a 28 French chest tube was guided through the uniportal incision for pleural drainage. The chest tube (Thopaz+, Medela AG, Switzerland) was removed from the day of surgery if air leakage was less than 40 mL/min for 4 hours without air spikes during mobilization regardless of fluid production (without blood or chyle fluids).

Performance measures

To assess the anatomical validity of the 3D lung reconstruction and added value in preoperative planning of the procedure, the 3D segmented pulmonary structures [i.e., pulmonary arteries and veins, bronchi up to the 3rd generation according to the Weibel's model (19), and segmental nodule location] and planned surgical approach were compared with preoperative findings based on the conventional 2D CT scan and intraoperative findings. First, one of the two dedicated thoracic surgeons, or surgical resident who was scheduled to perform the surgery, was requested to assess the pulmonary anatomical structures and prepare the surgical plan using 2D CT imaging. Surgeons had the option of evaluating the CT scan in axial, sagittal, and/or coronal cross-sections based on their preferences. The target segment or lobe in which the lung nodule was located had to be evaluated, as well as the number of arteries that run towards the target segment or lobe that had to be transected, the presence of any anatomical variations, and the subsequent surgical steps of the procedure taking the bronchus-artery-vein relation into account. Second, the same surgeon assessed the abovementioned anatomical aspects using the 3D lung reconstruction. After the surgical procedure, the preoperative 3D pulmonary anatomical structures were compared with the intraoperative findings, and any errors or limitations of the 3D lung reconstructions were identified and discussed. In case no discrepancies were mentioned by the surgeons after surgery, we assumed the pre-surgical answers based on the 3D lung reconstruction were valid. Moreover, the surgeons were asked to report whether they would like to have used the 3D lung reconstruction during surgery via a tablet, to evaluate its potential value during surgery.

Usability questionnaire

The surgeons assessed the 3D lung reconstructions via the 3D Slicer software utilizing 3D rotations, zooming function, and the transparency function per anatomical structure. The usability of the 3D lung reconstructions developed with 3D Slicer software was evaluated after the surgical procedure by one of the two dedicated thoracic surgeons who performed the surgery using the SUS questionnaire (see Table S1) (16,17). This ten-part scale provides a global view of the subjective assessment of usability per 3D lung reconstruction. The questions were graded on a scale from 1 (strongly disagree) to 5 (strongly agree), with a total score ranging between 0 and 100. A usability score above 68 was considered above average (23). Since there is no validated Dutch translation of the SUS yet, the English SUS questionnaire was used.

Data collection

Patient characteristics, including age, sex, Eastern Cooperative Oncology Group (ECOG) performance status, body mass index, American Society of Anesthesiologists classification, forced expiratory volume in 1 second (FEV1), diffusion capacity of the lung for carbon monoxide by the single-breath technique (DLCO-SB), intoxications, clinical Tumor Nodule Metastasis (TNM) classification 8th edition, previous thoracic surgery, and comorbidities were extracted from patient records. The following perioperative and postoperative data were collected: surgical approach, planned lung resection, performed lung resection, surgery duration, conversion, blood loss, surgery difficulty, the radicality of resection, pathological TNM classification 8th edition, tumor size, final pathology, drain duration, length of hospital stay, and complications within 30 days of surgery. The difficulty of the surgical procedure was assessed by the thoracic surgeon and rated on a 5-point Likert scale from 1 (very easy) to 5 (very difficult). Length of hospital stay was defined as the number of days between the first day after surgery and the day the patient was clinically discharged.

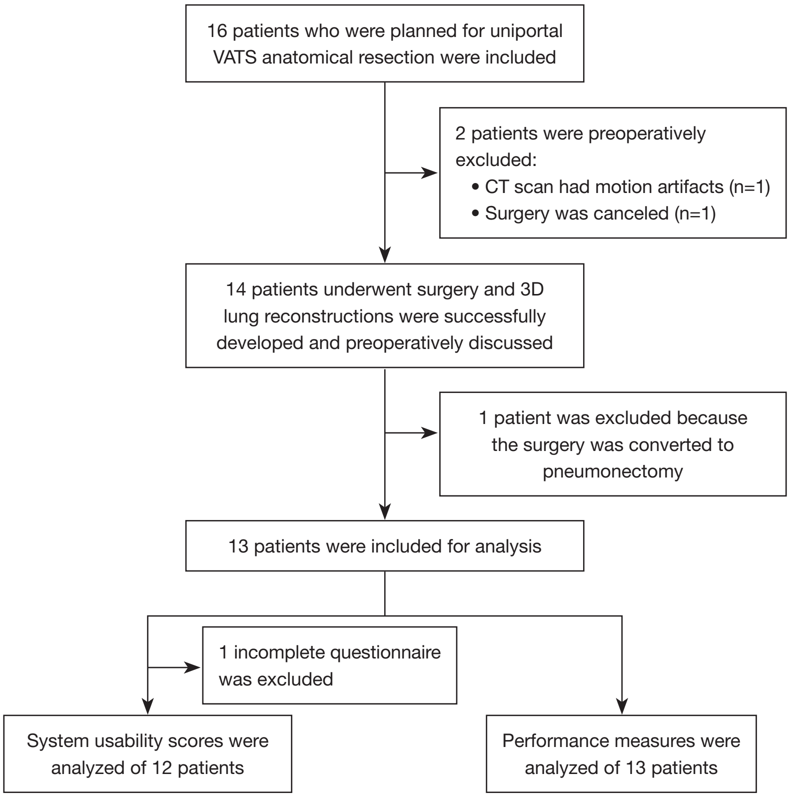

Figure 2 Patient inclusion flowchart. VATS, video-assisted thoracoscopic surgery; 3D, 3-dimensional; CT, computed tomography.

Statistical analyses

Statistical analyses were performed in IBM SPSS Statistics v28 (MacOS, Armonk, New York, USA). If data were normally distributed, based on the Shapiro-Wilk test, mean and standard deviation (SD) were reported, otherwise, data were reported using median and (25th and 75th percentiles). The SUS questionnaire score was calculated according to Brooke [1995] (16); the even-numbered questions contributed to the scale position 5 minus the scale position, while the odd-numbered questions contributed to the scale position minus 1. The final score was calculated by the sum of the even and uneven-numbered questions, multiplied by 2.5. Missing data were reported as such.

Results

A total of 16 patients who were scheduled for uniportal VATS lobectomy or segmentectomy were eligible for participation. One patient was preoperatively excluded as the CT scan contained motion artifacts (n=1). Two patients were excluded from our study because the surgery was canceled (n=1), or the surgery was intraoperatively converted to a pneumonectomy (n=1). Finally, as one questionnaire was incomplete (n=1), a total of 12 patients were included for our primary outcome usability, and 13 patients for the performance analysis. *Figure 2* presents the patient inclusion flowchart.

Three-dimensional lung reconstructions

An approximate 60 to 90 minutes was required to reconstruct one 3D lung reconstruction. An example of a 3D lung reconstruction (patient 6) is shown in *Figure 3*.

Perioperative patient characteristics

Preoperative patient characteristics are summarized in *Table 2*. In total, six males and seven females were included with a mean age of 68.2 years (SD =11.0) and a mean BMI of 26.6 kg/m^2 (SD =3.0). Preoperative lung function tests showed a mean FEV1 of 91.6% (SD =18.6) and DLCO-SB of 69.0% (SD =15.5).

An overview of the intraoperative and postoperative outcomes, including the difficulty of the surgery,

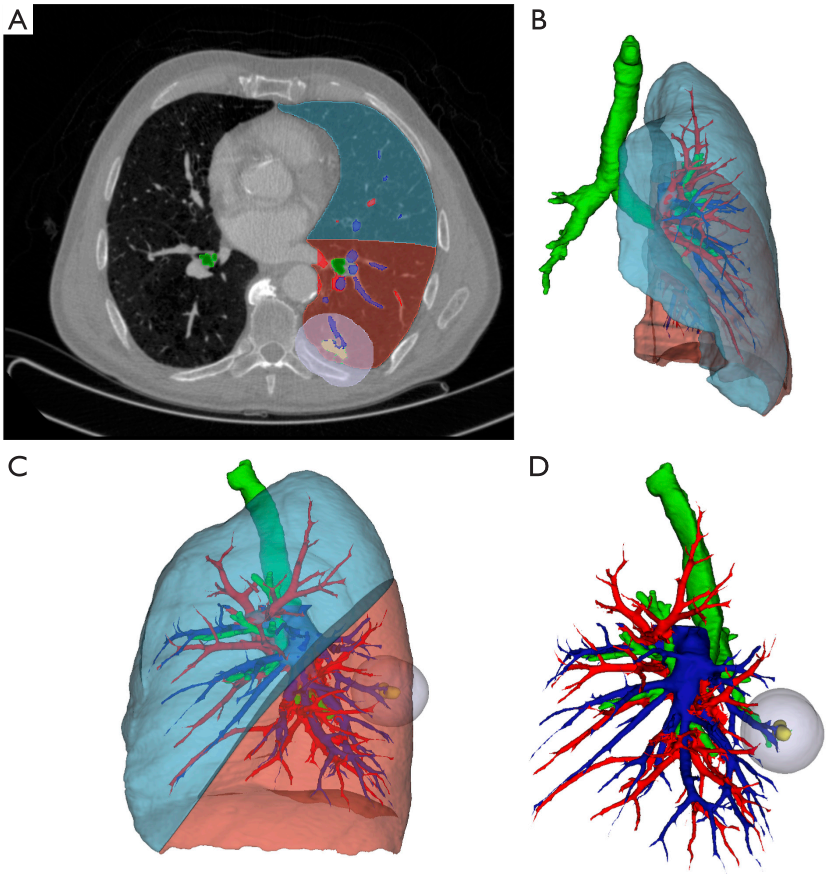

Figure 3 Preoperative 3D lung reconstruction of patient 6. Segmentations of the left upper lobe (transparent blue), left lower lobe (transparent red), airway (green), pulmonary arteries (blue), pulmonary veins (red), lung nodule (yellow), and surgical safety margin (transparent grey) were visualized in an axial slice of the CT scan (A), 3D view in the anterior direction (B), 3D view in the lateral direction (C), and 3D view in lateral direction without segmentations of the lobes (D). All elements in this figure are original. 3D, 3-dimensional; CT, computed tomography.

is demonstrated in Table S2. One segmentectomy (Table S2) and 12 lobectomies were performed. Twelve procedures were performed via uniportal VATS and one was started as a uniportal VATS procedure but converted to a thoracotomy due to the presence of extensive pleural adhesions following a recent lung infection. Complications were present in five patients. In total, three patients were readmitted. Two patients were readmitted with subcutaneous emphysema, one of whom experienced symptomatic subcutaneous emphysema with dyspnea. Both patients were observed at the ward and after two and five days respectively, the subcutaneous emphysema resolved spontaneously without the need for surgical intervention. One patient was readmitted with pleural empyema which was surgically evacuated. After this reoperation, the same patient experienced prolonged air leakage (twelve days) due to a technical failure of the drainage system (defective chest tube) and had a vacuum-assisted closure device placed for a wound infection of the thoracotomy incision. Furthermore, one patient was diagnosed with a urinary tract infection, and one experienced prolonged air leakage of more than five days. There were no 30-day mortalities. Pathological examination demonstrated that all resected lung nodules were primary lung tumors and confirmed complete resection (R0) in each of them (100%).

Performance measures

Performance measures per patient are summarized in *Table 3*. Three-dimensional lung reconstructions provided

Table 2 Preoperative patient characteristics

Patient	Sex	Age (years)	Comorbidities	Smoking history	ECOG	ASA	BMI (kg/m^2)	FEV1 (%)	DLCO SB (%)	Clinical TNM8	Previous thoracic surgery	Planned lung resection
1	Female	69	No	Smoker	2	3	27.2	87	54	cT1cN1M0	Wedge left lower lobe uniportal VATS	Lobectomy RLL + wedge RML
2	Female	63	No	No	0	2	29.7	100	62	cT1bN0M0	No	Lobectomy RLL
3	Female	68	No	Smoker	0	2	20.6	111	73	cT2bN0M0	No	Sleeve lobectomy RUL
4	Female	81	COPD GOLD II	History of smoking	1	3	24.2	63	54	cT1bN0M0	No	Segmentectomy S2 right
5	Female	52	No	History of smoking	0	2	24.7	112	85	cT2bN0M0	No	Lobectomy RLL and lymphatic fluid removal
6	Male	81	GOPD GOLD I	Smoker	1	3	24.8	103	63	cT1cN0M0	Segmentectomy S1-2 R uniportal VATS	Lobectomy LLL
7	Male	67	No	History of smoking	1	3	27.2	100	102	cT1bN0M0	No	Lobectomy RUL
8	Male	77	No	History of smoking	0	2	27.8	102	81	cT1cN0M0	No	Frozen wedge-resection RUL and completion lobectomy RUL
9	Female	58	No	Smoker	0	3	28.7	89	69	cT1bN0M0	Uniportal VATS wedge resection RUL	Completion lobectomy RUL
10	Male	81	No	History of smoking	1	3	32.1	112	77	cT3N0M0	No	Lobectomy LLL
11	Male	67	Asthma, ILD	History of smoking and cannabis	2	3	28.7	54	60	cT2bN0M0	No	Lobectomy LLL
12	Male	75	No	Smoker	1	3	23.6	78	NR	cT3N0M0	No	Lobectomy LUL
13	Female	47	COPD GOLD I	Smoker	0	3	26.6	80	48	cT3N0M0	No	Lobectomy LUL

ECOG, Eastern Cooperative Oncology Group; ASA, American Society of Anesthesiologists; BMI, body mass index; FEV1, forced expiratory volume in 1 second; DLCO SB, diffusion capacity of the lung for carbon monoxide by single breath; TNM8, Tumor Node Metastasis classification 8th edition; VATS, video-assisted thoracoscopic surgery; RLL, right lower lobe; RML, right middle lobe; RUL, right upper lobe; COPD, chronic obstructive pulmonary disease; GOLD, Global Initiative for Chronic Obstructive Lung Disease; LLL, left lower lobe; LUL, left upper lobe; ILD, interstitial lung disease; NR, not reported.

more accurate information on the segmental location of the lung nodule in 38% of the patients (5/13). In one of these patients, the tumor was centrally located, and therefore only the lobar location of the lung nodule was reported. In addition, the surgeons mentioned that they would have altered the surgical plan of eight patients based on the insights gained from the 3D lung reconstructions. The majority of the suggested alterations included repositioning the conventional planned transection planes of the bronchial and pulmonary vascular structures (n=7).

Furthermore, some preoperative 3D lung reconstructions showed anatomical patient-specific variations in eight of the 13 patients (62%) of which two major anatomical variations (patients 8 and 9). These included primarily pulmonary artery variations (n=7) and a single vein-bronchus variation wherein a segmental vein crossed the RUL bronchus inferiorly instead of the opposite expected anatomy. These variations were confirmed intraoperatively but not noticed on the corresponding 2D CT scan. One 3D lung reconstruction did not fully correspond with the intraoperative findings. In this case, the 3D reconstruction seemed to have missed an arterial segmental branch of the A6 artery which crossed the fissure into the upper lobe. In retrospect, this segmental A6 branch was present in the

Table 3 Usability and performance results of 3D lung reconstructions compared to 2D CT scan and intraoperative findings

Patient	Performed lung resection	Usability (SUS)	Lung nodule location			Number of arteries towards target segment/lobe			Presence anatomical variations			3D lung reconstruction	
			CT	3D	Operative confirmation	CT	3D	Operative confirmation	CT	3D	Operative confirmation	Potential change of surgery	Operative use
1	Lobectomy RLL + wedge RML	92.5	S8 or S9	Segmental border S8-9	Yes	3	3	Yes	NA	A6 splits at A4-5 level. No V6	Yes	Yes, stapling of arterial branches to RLL is possible in one attempt without narrowing/occlusion of middle lobe artery	No
2	Lobectomy RLL	95	S9 or S10	S10	Yes	1	2	Yes	NA	A6 at same level as A4-5, A9-10 and A7-8	Yes	Yes, dissection of pulmonary vein more peripherally for clipping V10	No
3	Lobectomy RUL	87.5	RUL	RUL	Yes	NA†	NA†	Yes	NA†	NA†	Yes	Yes, upfront lobectomy instead of sleeve expected	No
4	Segmentectomy S2 right	92.5	S2 or S1	S2	Yes	NA	2	Yes	NA	A2 originates out of truncus	Yes	Yes, resection of only S2, and additional transection of A2 via truncus necessary	No
5	Lobectomy RLL and lymphatic fluid removal	67.5	S6-9-10	S6 and S9	Yes	2	4	No (A6 missing)	None	Ascending A2 in RUL	Yes	No	No
6	Lobectomy LLL	92.5	S10	S10	Yes	1	1	Yes	None	None	Yes	No	No
7	Lobectomy RUL	77.5	S8	S8	Yes	2	2	Yes	NA	None	Yes	No	No
8	Lobectomy RUL	67.5	Segmental border S1-2	S2, resection margin in S1	Yes	2	2	Yes	NA	Elongated common arterial trunk and separate A2 branch	Yes	Yes, additional A2 branch	No
9	Lobectomy RUL	92.5	S1	S1	Yes	2	3	Yes	NA	Segmental vein crossed the RUL bronchus inferiorly. No common venous truncus	Yes	Yes, not necessary to identify the lower vein by dissection	Yes
10	Lobectomy LLL	82.5	S6-8	S6-8	Yes	NA	NA	Yes	NA	None	Yes	No	No
11	Lobectomy LLL	92.5	S8	S8	Yes	2	2	Yes	None	None	Yes	No	No
12	Lobectomy LUL	NR	S1-2	S3-4	Yes	NA	5–6	Yes	NA	A3 splits at a more caudal level	Yes	Yes, A3 dissection from within fissure	Yes
13	Lobectomy LUL	85	S1-2	S1-2-3	Yes	NA	4	Yes	NA	4 artery branches A3, A1-2, 1 posterior ascending artery, and A4-5	Yes	Yes, more accurate dissection plan for pulmonary artery branches	No

†, not assessable due to centrally located tumor. 2D, 2-dimensional; 3D, 3-dimensional; CT, computed tomography; SUS, system usability score; RLL, right lower lobe; RML, right middle lobe; A, artery; S, segment; V, vein; LLL, left lower lobe; NA, not assessable; LUL, left upper lobe; RUL, right upper lobe; NR, not reported.

3D lung model, however, its diameter was too small to be visually detectable in the 3D overview. In addition, this artery branch was not recognized by the surgeon on the corresponding 2D CT scan, although in retrospect, this artery branch was evident.

Usability questionnaire

The system usability questionnaire of 12 out of 13 lung reconstructions was scored (*Table 3*) and had a median SUS of 90.0 [interquartile range (IQR) =13.8]. Eighty-three percent of the 3D lung reconstructions (n=10/12) were scored above average (SUS >68).

Discussion

We investigated the usability and performance of 3D lung reconstructions for preoperative planning of uniportal VATS anatomical lung resections using the open-source software 3D Slicer compared to the conventional 2D assessment based on the CT scan. The developed 3D lung reconstructions satisfied the surgeons' requirements (*Table 1*) and, showed to be usable in the clinical setting. In terms of performance, 3D lung reconstructions provided more accurate segmental lung nodule locations and identified several anatomical variations.

Our pilot study is the first study that quantified the usability of preoperative 3D lung reconstructions with the worldwide used SUS questionnaire. Limited studies reported on usability outcomes of 3D lung reconstructions which were displayed via a portable computer or tablet. So far, only Qiu *et al.* [2020] and Sadeghi *et al.* [2021] reported on the usability with subjective questionnaires or interviews for preoperative planning of 3D printed models compared with 3D reconstructions, and virtual reality, respectively (24,25). Based on our results, 3D lung reconstructions computed with the open-source 3D Slicer software seem to be usable in clinical practice.

Similar studies using predominantly commercially available software programs report accuracy percentages of identifying pulmonary arteries between 79% and 100% (9,10,26). The performance of our open-source 3D Slicer-computed 3D lung reconstructions in the clinical setting was similar to or even better, as only a single segmental pulmonary artery branch (A6) was preoperatively not identified in the 3D lung reconstruction by the surgeon in the 3D view of 3D Slicer because of its small diameter. Consequently, the protocol could be adjusted by adding an additional margin of a few millimeters to the vessel segmentations, at the discretion of the user. Our results were similar to the percentages reported in the literature regarding accuracy percentages of the identification of the pulmonary veins (between 80% and 100%) (9,10,26), as well as accurate lung nodule location (between 98–100%) (12,27). Although our sample size is limited, the results of our preoperative 3D lung reconstructions developed with 3D Slicer software are promising.

Our study reported on 3D lung reconstructions for both lobectomy and segmentectomy, while these reconstructions are recommended as a technical standard for segmentectomies in specific (8). Qiu *et al.* [2020] demonstrated that the impact of 3D lung reconstructions may be of limited added value in surgical planning and intraoperative guidance for simple segmentectomies compared to complex ones, and may not compensate for the time and cost involved in the development of these 3D lung reconstructions (25). This might be true regarding the lung nodule location, however, the importance and the presence of anatomical variations at the lobar level should not be underestimated. Serious complications such as major bleeding could be prevented if the anatomy is known preoperatively (13). Furthermore, Zhang *et al.* [2019] reported a reduction in surgery duration and blood loss, when using 3D lung reconstructions for preoperative planning of a uniportal VATS lobectomy compared to conventional CT (13). In our study, the transection planes of 54% of the cases (n=7/13) would be changed based on the presence of anatomical variations, suggesting that 3D lung reconstructions computed with 3D Slicer can have a considerable impact on preoperative planning of uniportal VATS lobectomy as well.

While the impact of the use of 3D reconstructions on clinical outcomes falls outside the scope of our pilot study, several recent studies report significant improvements in clinical outcomes. A recent meta-analysis by Xiang *et al.* [2022] reported that the use of 3D lung reconstructions for thoracoscopic segmentectomies resulted in promising short-term clinical outcomes compared to the use of the conventional CT scan, including a significant decrease in blood loss, surgery duration, conversion rate, hospital stay, and total number of complications (14). Furthermore, the mean surgery duration could significantly be reduced to 30 minutes using a 3D lung reconstruction (28). Long-term evidence on the use of 3D lung reconstructions are limited.

Apart from the limited sample size, there were several other limitations to our pilot study. First, the time to create a 3D lung reconstruction took about 60 to 90 minutes. The main reason for the relatively long time to reconstruct the 3D lung models was the semi-automatic nature of the proposed 3D Slicer protocol and the use of diagnostic late arterial phase contrast-enhanced 2D CT scans, also known as the early venous portal phase. These 2D CT scans show optimal enhancement of the hilar structures for TNM staging (29), however, this also challenges the discrimination between pulmonary arteries and veins as they are often intertwined. Adding an early arterial-phased CT scan (e.g., CT pulmonary angiogram) could prevent the intertwining of the pulmonary artery and vein segmentations and reduce the computation time by 30 minutes. On the other hand, the use of artificial intelligence (AI)-based applications could be helpful to decrease the computation time to only two minutes (26,30). Notwithstanding, even with the use of AI, a thorough evaluation of the created lung reconstruction would still be necessary by a colleague with sufficient knowledge of lung anatomy (26), and in case of inaccuracies, the model has still to be (manually) adjusted in a segmentation software program. It is possible, however, to incorporate open-source AI-trained models into 3D Slicer via the Python extension, for example, and thereby provide for more automated segmentation processing as opposed to semiautomatic tools, reducing computation time whilst enabling in-house manual adjustments. Second, our study did not demonstrate the non-inferiority of this technique compared to other (commercially) available software. Nevertheless, the usability and performance of 3D Slicer for preoperative planning of VATS anatomical resections were not evaluated before. As our study showed the promising potential of 3D-Slicer for preoperative 3D lung reconstructions in a clinical setting, future research should investigate its non-inferiority regarding performance and subsequent potential clinical consequences compared to other (commercially) available software. Lastly, as mentioned before, the small sample size is a major limitation. We were not able to perform any statistical tests and interobserver agreement analyses; however, this study was designed to assess whether the 3D lung reconstructions were usable and functional in a clinical setting. Statistical comparisons and interobserver agreements should be subject to future larger-sized studies. In addition, our study population only included one segmentectomy, as opposed to 12 lobectomies. Aside from a larger scale study, the number of segmentectomies should at least be comparable to the number of lobectomies in future studies.

Three-dimensional lung reconstructions using the open-source 3D Slicer software seem to have the potential to be usable in the clinical setting for preoperative planning of uniportal VATS anatomical resections based on our pilot study. It was also relatively easy to learn and train technical physician students to develop these 3D lung reconstructions based on an in-house step-by-step 3D Slicer protocol. The student mentioned he was able to develop these 3D lung reconstructions on his own after four 3D lung reconstructions. In addition, using open-source software such as 3D Slicer, self-developed applications can be computed in other programming and numeric computing platforms including MATLAB (The Mathworks Inc., Natick, Massachusetts, USA) or Python (Python Software Foundation), for example, a pulmonary vessel segmentation method specific for our hospital-specific CT scan settings to decrease the time to create a 3D lung reconstruction.

Besides using these 3D reconstructions for preoperative planning, these reconstructions can also be useful for clinical teaching and training of residents in thoracic surgery (10,30). Residents reported higher scores in understanding the segmental structures and surgical process of segmental resection, as well as an increase in learning enthusiasm and interest (30).

The usability of the 3D lung reconstructions in a clinical setting could be further increased by incorporating additional applications or visualizing these reconstructions using other advanced imaging modalities. First, a preoperative visualization of the intersegmental plane would be helpful. Besides the current identification methods to visualize intersegmental planes intraoperatively, such as the inflation-deflation method and the use of systemic indocyanine green (22), preoperative knowledge of the intersegmental planes can assist in determining whether a segmentectomy provides sufficient surgical free margin around the resected tumor to ensure non-inferior oncological outcomes (7,22). Second, simulation of the surgical resection could be helpful in preoperative planning of the transection planes (10), as well as for training residents potentially decreasing the learning curve (10,30). In terms of advanced imaging modalities, several studies have demonstrated that virtual reality with 3D glasses (24), 3D printed models (11,25), and augmented reality (11), might provide for an even better understanding of the pulmonary anatomy (25). These advanced image modalities, however, are more expensive.

Conclusions

In conclusion, our pilot study demonstrated that 3D lung reconstructions developed with our in-house protocol using the open-source semi-automatic software 3D Slicer can be usable in clinical settings and provided accurate performance for preoperative planning of uniportal VATS lobectomy and segmentectomy. Larger-scaled comparative studies should be conducted to confirm whether these 3D lung reconstructions using the 3D Slicer software tools are beneficial for preoperative planning of an anatomical resection and will result in improved patient outcomes, as compared to conventional planning or 3D preoperative planning with other (commercial) software programs.

Acknowledgments

We would like to thank the following technical physician students for their contribution to the development of the in-house 3D Slicer protocol: Renske Brekelmans, Dagmar M.C. Eek, Megan E.H. Scheers, Sara L. Schooten, Rosalie M. Dekkers, Dionne A.W. Smeets, Mijna G.A. Vos, and Guido S. Wiersma. Part of the contents of this study have been presented on the following webpage: https://ichgcp.net/clinical-trials-registry/NCT06132607.
Funding: None.

Footnote

Reporting Checklist: The authors have completed the CONSORT extension Pilot and Feasibility trial reporting checklist. Available at https://tlcr.amegroups.com/article/view/10.21037/tlcr-24-134/rc

Trial Protocol: Available at https://tlcr.amegroups.com/article/view/10.21037/tlcr-24-134/tp

Data Sharing Statement: Available at https://tlcr.amegroups.com/article/view/10.21037/tlcr-24-134/dss

Peer Review File: Available at https://tlcr.amegroups.com/article/view/10.21037/tlcr-24-134/prf

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://tlcr.amegroups.com/article/view/10.21037/tlcr-24-134/coif). K.W.E.H., Y.L.J.V. and E.R.d.L. received consulting fees from Johnson & Johnson for education in uniportal VATS lobectomy. K.W.E.H. is a board member of the Dutch Federation of Medical Specialists. The other authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Institutional Medical Ethical Review Committee of Zuyderland and Zuyd University of Applied Sciences (No. 20220105) and informed consent was obtained from all individual participants.

References

1. Yamashita S, Goto T, Mori T, et al. Video-assisted thoracic surgery for lung cancer: republication of a systematic review and a proposal by the guidelines committee of the Japanese Association for Chest Surgery 2014. Gen Thorac Cardiovasc Surg 2014;62:701-5.
2. Batchelor TJP, Rasburn NJ, Abdelnour-Berchtold E, et al. Guidelines for enhanced recovery after lung surgery: recommendations of the Enhanced Recovery After Surgery (ERAS®) Society and the European Society of Thoracic Surgeons (ESTS). Eur J Cardiothorac Surg 2019;55:91-115.
3. Ginsberg RJ, Rubinstein LV. Randomized trial of lobectomy versus limited resection for T1 N0 non-small cell lung cancer. Lung Cancer Study Group. Ann Thorac Surg 1995;60:615-23.
4. Saji H, Okada M, Tsuboi M, et al. Segmentectomy versus lobectomy in small-sized peripheral non-small-cell lung cancer (JCOG0802/WJOG4607L): a multicentre, open-label, phase 3, randomised, controlled, non-inferiority trial. Lancet 2022;399:1607-17.

5. Altorki N, Wang X, Kozono D, et al. Lobar or Sublobar Resection for Peripheral Stage IA Non-Small-Cell Lung Cancer. N Engl J Med 2023;388:489-98.
6. Wang X, Guo H, Hu Q, et al. Pulmonary function after segmentectomy versus lobectomy in patients with early-stage non-small-cell lung cancer: a meta-analysis. J Int Med Res 2021;49:3000605211044204.
7. Eguchi T, Sato T, Shimizu K. Technical Advances in Segmentectomy for Lung Cancer: A Minimally Invasive Strategy for Deep, Small, and Impalpable Tumors. Cancers (Basel) 2021;13:3137.
8. Brunelli A, Decaluwe H, Gonzalez M, et al. European Society of Thoracic Surgeons expert consensus recommendations on technical standards of segmentectomy for primary lung cancer. Eur J Cardiothorac Surg 2023;63:ezad224.
9. Akiba T, Marushima H, Harada J, et al. Importance of preoperative imaging with 64-row three-dimensional multidetector computed tomography for safer video-assisted thoracic surgery in lung cancer. Surg Today 2009;39:844-7.
10. Tokuno J, Chen-Yoshikawa TF, Nakao M, et al. Resection Process Map: A novel dynamic simulation system for pulmonary resection. J Thorac Cardiovasc Surg 2020;159:1130-8.
11. Li C, Zheng B, Yu Q, et al. Augmented Reality and 3-Dimensional Printing Technologies for Guiding Complex Thoracoscopic Surgery. Ann Thorac Surg 2021;112:1624-31.
12. Ji Y, Zhang T, Yang L, et al. The effectiveness of three-dimensional reconstruction in the localization of multiple nodules in lung specimens: a prospective cohort study. Transl Lung Cancer Res 2021;10:1474-83.
13. Zhang M, Liu D, Wu W, et al. Preoperative 3D-CT bronchography and angiography facilitates single-direction uniportal thoracoscopic anatomic lobectomy. Ann Transl Med 2019;7:526.
14. Xiang Z, Wu B, Zhang X, et al. Preoperative Three-Dimensional Lung Simulation Before Thoracoscopic Anatomical Segmentectomy for Lung Cancer: A Systematic Review and Meta-Analysis. Front Surg 2022;9:856293.
15. Rice D. Step-By-Step Guide to 3D Segmentation of Tumor, Airways, and Vessels for Preoperative Planning for Anatomic Segmentectomy Using 3D Slicer. Cardiothorac Surg Netw 2023 Oct 27.
16. Brooke J. SUS: a 'quick and dirty' usability. In: Jordan PW, Thomas B, McClelland IL, et al., editors. Usability Evaluation In Industry. London: CRC Press 1996:189-94.
17. Hyzy M, Bond R, Mulvenna M, et al. System Usability Scale Benchmarking for Digital Health Apps: Meta-analysis. JMIR Mhealth Uhealth 2022;10:e37290.
18. Julious SA. Sample size of 12 per group rule of thumb for a pilot study. Pharm Stat 2005;4:287-91.
19. Weibel ER, Gomez DM. Architecture of the human lung. Use of quantitative methods establishes fundamental relations between size and number of lung structures. Science 1962;137:577-85.
20. Pinter C, Lasso A, Fichtinger G. Polymorph segmentation representation for medical image computing. Comput Methods Programs Biomed 2019;171:19-26.
21. Yip SSF, Parmar C, Blezek D, et al. Application of the 3D slicer chest imaging platform segmentation algorithm for large lung nodule delineation. PLoS One 2017;12:e0178944.
22. Andolfi M, Potenza R, Seguin-Givelet A, et al. Identification of the intersegmental plane during thoracoscopic segmentectomy: state of the art. Interact Cardiovasc Thorac Surg 2020;30:329-36.
23. Lewis JR, Sauro J. Item benchmarks for the system usability scale. J Usability Stud 2018;13:158-67.
24. Sadeghi AH, Maat APWM, Taverne YJHJ, et al. Virtual reality and artificial intelligence for 3-dimensional planning of lung segmentectomies. JTCVS Tech 2021;7:309-21.
25. Qiu B, Ji Y, He H, et al. Three-dimensional reconstruction/personalized three-dimensional printed model for thoracoscopic anatomical partial-lobectomy in stage I lung cancer: a retrospective study. Transl Lung Cancer Res 2020;9:1235-46.
26. Chen X, Wang Z, Qi Q, et al. A fully automated noncontrast CT 3-D reconstruction algorithm enabled accurate anatomical demonstration for lung segmentectomy. Thorac Cancer 2022;13:795-803.
27. Hu CG, Yang XT, Zhao M, et al. Three-Dimensional Computed Tomography Bronchography and Angiography-Guided Thoracoscopic Segmentectomy for Pulmonary Nodules. Surg Innov 2022;29:343-52.
28. Chen Y, Zhang J, Chen Q, et al. Three-dimensional printing technology for localised thoracoscopic segmental resection for lung cancer: a quasi-randomised clinical trial. World J Surg Oncol 2020;18:223.
29. Larici AR, Franchi P, Del Ciello A, et al. Role of delayed

phase contrast-enhanced CT in the intra-thoracic staging of non-small cell lung cancer (NSCLC): What does it add? Eur J Radiol 2021;144:109983.
30. Deng X, Liu Y, Chen H. Three-dimensional image reconstruction based on improved U-net network for anatomy of pulmonary segmentectomy. Math Biosci Eng 2021;18:3313-22.

Cite this article as: Laven IEWG, Oosterhoff VPS, Franssen AJPM, van Roozendaal LM, Hulsewé KWE, Vissers YLJ, de Loos ER. Evaluating three-dimensional lung reconstructions for thoracoscopic lung resections using open-source software: a pilot study. Transl Lung Cancer Res 2024;13(7):1595-1608. doi: 10.21037/tlcr-24-134

