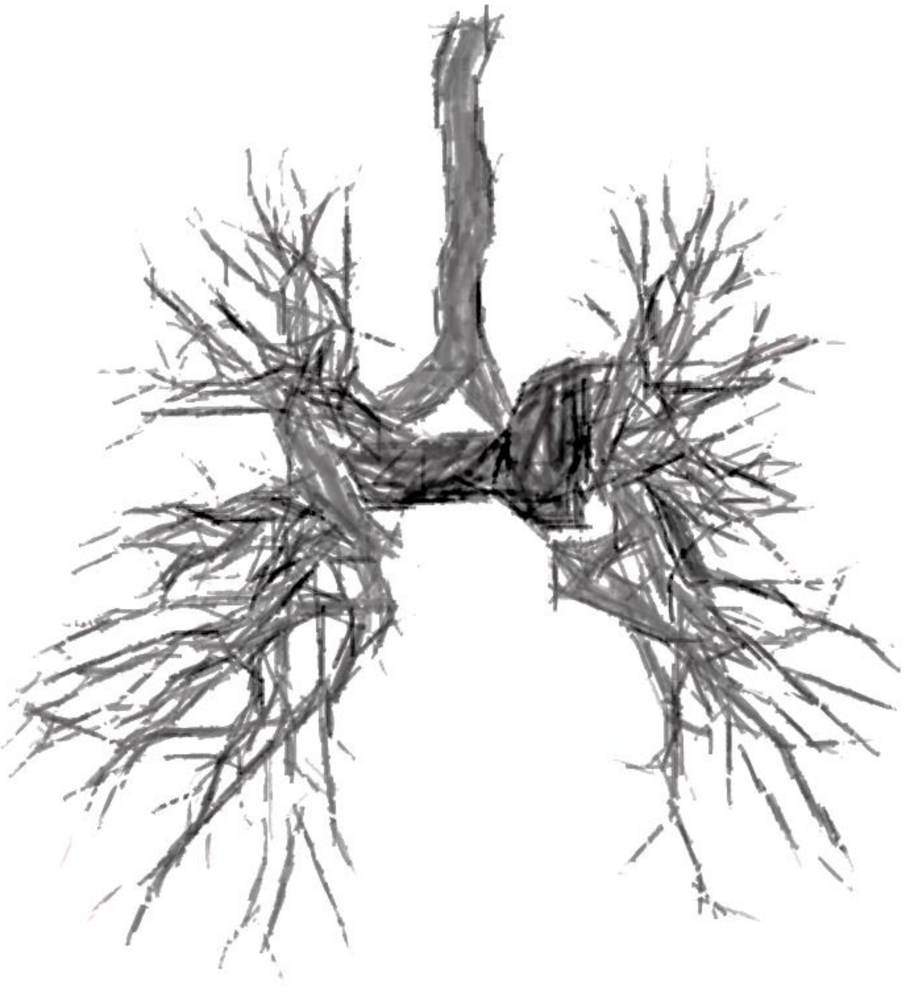
Development of a Three-Dimensional (3D) Model for Preoperative Planning of Lung Segmentectomies for Patients with Stage 1A Non-Small Cell Lung Cancer (NSCLC)



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Internship period:	16-10-2023 to 18-10-2024

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Thorax Centrum Twente MST

Acknowledgements

In March of 2023, I started my 3rd M2 internship at the department of cardiothoracic surgery in the Thorax Centrum Twente at the Medisch Spectrum Twente, Enschede. At the time, the idea of creating preoperative 3D models for segmentectomy was still in its infancy, with only 2 M2 students having previously worked on the project. The production of a 3D model of the pulmonary anatomy, at that time, took 2 days. During my internship, I laid the groundwork for what would become the segmentation protocol included in this research.

As I left for my final internship, I could not stop thinking of the project that I had done at the MST and the possibility set up a new use for 3D visualisation. It is with this in mind that I contacted Frank Halfwerk with the idea of proceeding with the 3D-lung project at the MST as the subject of my M3 internship.

I would like to thank my family and friends for the unconditional support throughout the process of my graduation internship and master thesis.

I would like to thank Frank Halfwerk first and foremost for his enthusiasm and professionalism. As my technical medical supervisor on location, he was always up for a short brainstorming session and I am grateful for his support throughout my internship. His perspective on the practicality of technical innovation and always putting patient care first, helped me guide my decision-making throughout the year.

Bryan Martina, serving as my medical supervisor, has been instrumental in understanding the complex nature of anatomical resections. Whilst busy, he was always available for a quick chat about the project or surgical skills. He, as well as all the other cardiothoracic surgeons at the TCT, have been most inviting regarding clinical activities allowing me to practice and improve my surgical skills.

My Technical advisor, Françoise Siepel, I want to thank her for her critical view and, if a problem arose, thinking along with the process. I would also like to thank the rest of the personnel of the Robotics and Mechatronics group for the meetings, often producing new and exciting ideas to tackle technical problems.

I would like to thank Jutta Arens, and the entire EOST group for their input throughout the year at the meetings. You have made me feel welcome and offered valuable feedback throughout the year.

My sincere tanks goes out to Rob van Doremalen, who offered his time, effort, expertise and connections in order to further the research. I would also like to thank the 3D lab-staff for the accommodation of my project in their field of expertise.

I would like to thank Bryan Wermelink for his (prompt) availability to serve as an outside member of my graduation commission.

Finally, I would like to give thanks to my Process supervisor Bregje Sweep. She, along with my intervision group, have made it possible for me to reflect on my progress throughout my internships.

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Background: *For patients with a single local non-small celled lung carcinoma <2cm (stage 1A1-2) and poor pulmonary function, minimally invasive surgical removal of single or multiple lung segments (segmentectomy) might be considered as a treatment option. Three-dimensional (3D) models have shown added value in preoperative and intraoperative guidance of segmentectomies and can lead to essential changes in the surgical plan. Commercial services may provide preoperative models, yet these services are costly and require transfer of sensitive patient data to external entities. This article introduces an in-house segmentation method for the pulmonary structures using* [redacted]*). This paper aims to compare the new segmentation method to conventional 3D segmentation methods and access the added value of preoperative visualisation of the pulmonary anatomy for segmentectomies for patients with stage 1A NSCLC.*

Methods: *Patients that received a contrast-enhanced CT scan from 01-02-2024 until 29-02-2024 were modelled using* [redacted]*. Patients were excluded if no segmentectomy was performed during the inclusion period.*

Results: *In total 16 patients were included to make 3D models to compare the new segmentation method* [redacted]

Conclusion: *The new segmentation method produces adequate models for use in the preoperative planning of segmentectomies. The preoperative 3D models lead to* [redacted] *further research must investigate the clinical benefits of 3D-guided lung segmentectomies.*

Keywords- 3D visualisation, Segmentectomy, Video Assisted Thoracic Surgery, Questionnaire

1. Introduction

Lung cancer remains the leading cause of cancer-related mortality within the Netherlands. Annually, 14.300 patients are diagnosed with lung cancer in the Netherlands. 70% of all lung cancer diagnoses in the Netherlands are Non-small cell lung cancer (NSCLC) (1). Surgical resection is an effective curative option for early-stage NSCLC (I, II, IIIA). Surgical intervention for lung cancer in the Netherlands is primarily performed with the use of video-assisted thoracic surgery (VATS) (1). This is a minimally invasive surgery aimed at reducing surgical trauma and offering better survivability compared to traditional thoracotomy (2). A schematic illustration can be seen in Figure 1. A lobectomy is the gold standard for curative surgery within the Netherlands (3-7). For frail patients, however, sub-lobar resections offer good oncological outcomes whilst sparing lung volume (7).

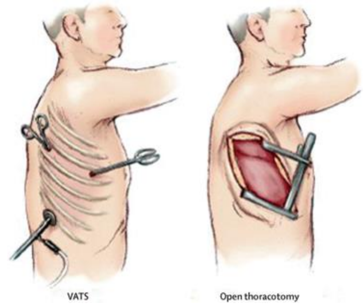

Figure 1: Schematic illustration of video-assisted thoracic surgery compared to a thoracotomy (8).

In 2023 segmentectomies were adopted in the Medisch Spectrum Twente (MST) as a treatment option for stage 1A NSCLC < 2 cm (1A1-2). Clinical stage 1A1 and 1A2 NSCLC know a high 60-month overall survival compared to higher staged NSCLC at 92% and 83% respectively (9). A segmentectomy (also known as an anatomical resection) is a sub-lobar resection involving the removal of lung parenchyma following anatomical lung segments (10). A lung segment constitutes a sub-lobar section of a lobe with its own bronchi and artery flanked by intersegmental veins, rendering each segment functionally independent (11). A schematic representation of a segment can be seen in Figure 2.

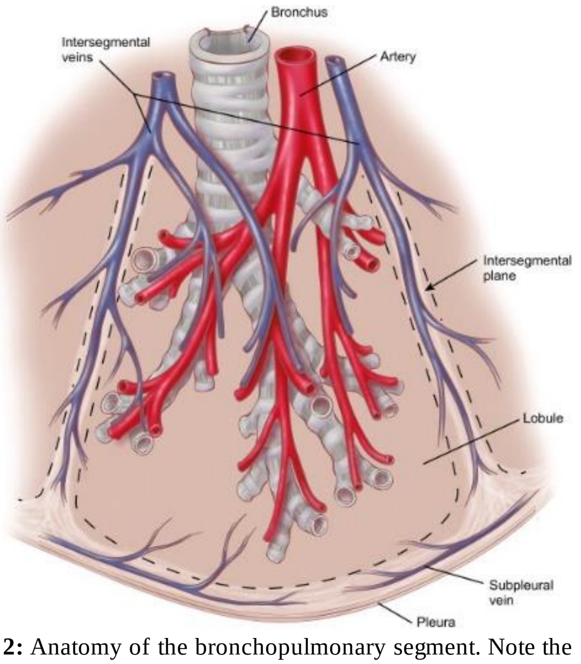

Figure 2: Anatomy of the bronchopulmonary segment. Note the segmental bronchus, artery and the draining pulmonary vein marking the intersegmental plane (11).

In principle, each lung has 10 segments, but on the left lung, the first two segments often share a common bronchial trunk and are often referred to as a single segment 1+2 (S1+2). Additionally, the segmental bronchus of segment 7 (B7) of the left lower lobe (LLL) is only present in 7.9% of cases, S7 is thus often omitted (11-13).

For patients with stage IA, segmentectomies offer a comparable 5-year survival compared to lobar resection (14). More recently, a randomized phase 3 trial revealed a significant advantage in the overall survival of patients with stage 1A NSCLC undergoing a segmentectomy compared to a lobectomy. There were however more local recurrences in the segmentectomy group (15). Compared to wedge resection, segmentectomies offer better oncological results, a higher probability of achieving an adequate surgical margin, and higher survival (16-18). Figure 3 shows a schematic illustration of the different types of resections available for patients with NSCLC.

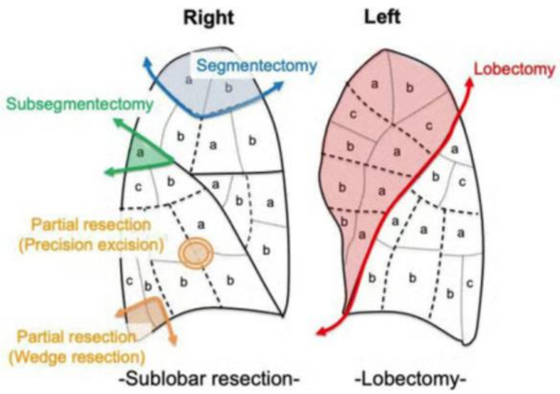

Figure 3: Surgical procedures for lung cancer treatment (19). With a lobectomy (red), a whole lung lobe is removed. With a wedge resection (yellow), a part of the lobe is removed with no consideration for the pulmonary anatomy. A segmentectomy (Blue) follows the intersegmental planes.

The complicated segmental anatomy, the wide array of anatomical variations, and the difficulty in localizing tumours make a segmentectomy a complex operation that necessitates an experienced operator thoroughly familiar with pulmonary anatomy (19). These challenges are further compounded by the endoscopic nature of the VATS technique, offering only a 2D representation with a limited field of view.

Currently, the target segment and the patient-specific anatomy are determined preoperatively using 2D CT scans with intravenous contrast. Although CT scans have a high resolution, it proves challenging to accurately determine the target segment due to the absence of anatomical landmarks marking the intersegmental plane. The three-dimensional (3D) modelling of pulmonary structures for preoperative planning has demonstrated added value in guiding accurate segmentectomies and has become a commonly used technology for these procedures (20, 21).

Models of the pulmonary anatomy can be made using either automatic or manual segmentation. Whilst automatic segmentation saves time, it is primarily based on AI models requiring a large amount of effort to produce a large enough dataset representing the possible morphologies of the pulmonary anatomy (22, 23). Additionally, these models can be vulnerable to overfitting. Manual segmentation can be done on commercially available or open-source software. The main downsides of manual segmentation are the time it takes to produce each model and the potential for human error or manipulation (24-26). At MST, the manual segmentation software [redacted] has been utilized for segmenting the pulmonary veins, arteries, bronchi, and lung lobes for preoperative visualization by Technical Medicine students. The current segmentation protocols are, however, too time-consuming or do not provide enough flexibility needed to segment the pulmonary structures with sufficient detail for each patient.

In this [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

2. Methods

2.1. A comparative evaluation of manual segmentation methods for preoperative visualisation of pulmonary structures for lung segmentectomies in regular CT Thorax scans with intravenous contrast

In the [redacted].

The research is structured following ‘the strengthening of the reporting of observational studies in epidemiology’ (STROBE) guidelines (27).

2.1.1.Study design

This study is designed as a cross-sectional cohort study. [redacted]

[redacted]

[redacted]

- [redacted]

[redacted]

[redacted]

Hypothesis: [redacted]

H0: [redacted]

2.1.2.Setting

Thorax CT scans with intravenous contrast and a slice thickness of 1 mm were collected from the radiology department at the MST. These scans were loaded into [redacted]

In each of the segmentations, [redacted]

2.1.3.Participants

All patients who received a Thorax CT scan with intravenous contrast in the period of 01-02-2024 to 29-02-2024 were included in the study. These patients were subsequently screened for the exclusion criteria listed in Table 1. The final study population of 16 patients were chosen at random out of the remaining CT scans.

Table 1. Exclusion criteria

Moderate-severe atelectasis
Moderate-severe pleural effusion
Moderate-severe pulmonary fibrosis
HU-value pulmonary trunk or left atrium <100
Lung emboli present

2.1.4. Image acquisition

Diagnostic late arterial phase contrast-enhanced CT Thorax scans were acquired. These scans were made with the Siemens SOMATOM Definition Flash CT system. The scans had a slice thickness of 1.0mm, no gantry tilt and a collimation distance of 0.6mm. The images were reconstructed using a Bf37f\2 reconstruction kernel. The scans were formatted into Digital Imaging and Communication in Medicine (DICOM) files before transfer to an external drive. Before selection, the scans were screened for the exclusion criteria in Itellispace (Philips V7.0).

[redacted]

Figure 4: Overview of [redacted]

2.1.5. Variables

The primary variables are [redacted]

[redacted]

[redacted]

- [redacted]
- [redacted]
- [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

2.1.6. Bias

When initially modelling both datasets, the researcher had more experience using the software from [redacted].

2.1.7. Study size

To calculate a sufficient number of participants to acquire a significant difference in [redacted]

2.1.8. Statistical methods

All study variables were analysed using descriptive statistics. As almost all data had a non-normal distribution, the descriptive data consists of the mean, the 25th, and 75th percentiles. The P value for [redacted] is calculated using a double-sided Friedmann test. A p-value <0.05 was deemed significant. If a measurement is found to be significant, the Hold-Bonferroni method is used to prevent type I errors and further pair-wise analysis is performed.

2.2. Three-dimensional modelling as a tool for preoperative planning of VATS Segmentectomies for patients with 1A1-2 NSCLC

Many methods of determining the quality of the pulmonary structures, especially the bronchi, have been developed. These methods are most often aimed at the number of generations, or total length and rarely consider if the structures that are visualized are clinically relevant. Sadeghi et al(29) reported that in 40% of cases, the surgical plan was adjusted due to a 3D-based evaluation of the anatomy. Bakhuis et al(30) showed in 52% of cases the surgical plan was adjusted after 3D VR-guided visualization of the broncho vasculature. This study aims to investigate the added clinical value of using and 3D model to the preoperative planning by evaluating the incidence of critical changes to the surgical plan and whether the pulmonary structures are sufficiently visualized using the current segmentation method using questionnaires. The research is structured following the STROBE guidelines (27).

2.2.1. Study design

In this retrospective study, 3D models were made using contrast-enhanced CT scans of patients who have undergone or have had lesions suitable for anatomical resection in the MST. To create 3D models of the pulmonary structures, the DICOM files were collected from the radiology department. These scans were used to make 3D models featuring the airway, lung parenchyma, the target tumour, pulmonary arteries, and pulmonary veins. An example of the resulting model can be seen in Figure 6.

To investigate the additional value of the 3D models for the preoperative planning of segmentectomies, surgeons first made a preoperative plan based on the conventional 2D CT scan. Sequentially, they made a new plan based on the 3D model of the identical patient. The answers given were documented in the form in appendix C. To investigate the usability of the model, feedback on the quality and usability of the model is gathered via a rubrics questionnaire. This questionnaire was developed by the researcher in collaboration with the 3D lab at the MST and can be found in Appendix D.

2.2.2. Participants

Patients who have undergone segmentectomies at the MST in 2023 were included. These patients were identified by searching the hospital system for all segmentectomies performed in the year 2023. In addition to this patient group, patients who were discussed as potential candidates for segmentectomies from 01-12-2023 until 26-07-2024 at the LMDO were included. Patients were excluded if no contrast-enhanced CT scans and a 1mm slice thickness were available.

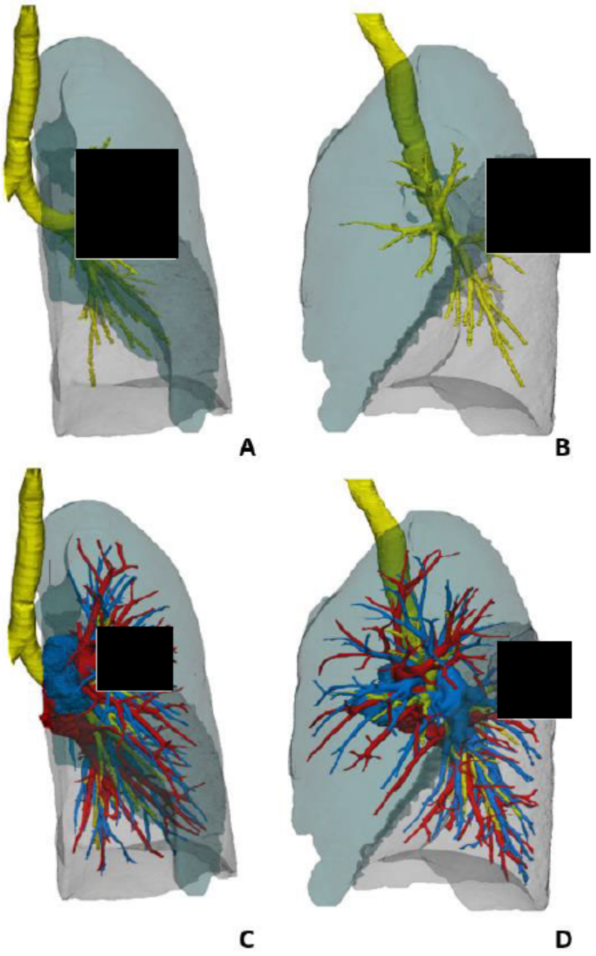

Figure 6: The 3D model of subject 7 with a lesion in the apex of the left lower lobe. A, B: Anterior and lateral view of airways (yellow), lung parenchyma (transparent blue and grey), and tumour with a 2cm tumour margin. C, D: Identical views with additional visualization of the pulmonary veins and arteries.

2.2.3.Preoperative 3D model

To produce a 3D model, the manual segmentation software [redacted] is used. The new segmentation protocol in Appendix A was used to make the models. The segmented structures are converted into 3D objects and transported to the 3-matic software in which they are color-coded according to the colours in Figure 6. [redacted] software is used to visualize the 3D model for evaluation.

2.2.4.Variables

The primary variable is [redacted]

The secondary variables are the [redacted]

2.2.5.Study size

The study size is determined by the number of patients with suitable preoperative CT scans who underwent a segmentectomy in 2023 or were presented as candidates for segmentectomy at the LMDO from 01-12-2023 until 26-07-2024.

2.2.6.Statistical Methods

Due to the limited number of eligible participants and surgeons, descriptive statistics are performed to analyse the data.

2.3. Prospective evaluation of 3D models for VATS segmentectomies for patients with stage 1A NSCLC

The research is structured following the STROBE guidelines (27).

2.3.1.Study Design

This study is designed as a cohort study. Patients who were marked as possible candidates for segmentectomy were modelled preoperatively. The main purpose of this study is to investigate the practical application of preoperative 3D models for segmentectomies in the MST and the added value that these models provide. The main research question is: Does preoperative modelling facilitate alterations in the intraoperative approach and identification of the relevant segmental structures for patients undergoing segmentectomies?

Hypothesis: The preoperative 3D visualization of the pulmonary structures leads to the alteration of the intraoperative approach and improves the ability of the surgeon to accurately identify the relevant structures.

H0: The preoperative 3D visualization of the pulmonary structures has no impact on the intraoperative approach and does not facilitate the intraoperative identification of relevant structures.

2.3.2.Setting

This study falls under an ongoing research protocol of the 3D lab and is excluded from the Human Subjects Act. To incorporate the use of a 3D model into the clinical workflow, patient consent was gathered preoperatively. After a patient was discussed as a potential candidate for a segmentectomy, a 3D model was made using the most recent CT scan with contrast. The model was accessed prior to surgery. Additionally, the researcher was present during surgery to show the model intraoperatively if needed. Endoscopic images were collected during surgery, and later compared to the model, Additionally, a workflow for the integration of the 3D models into the clinical setting was established. This workflow can be seen in Figure 7.

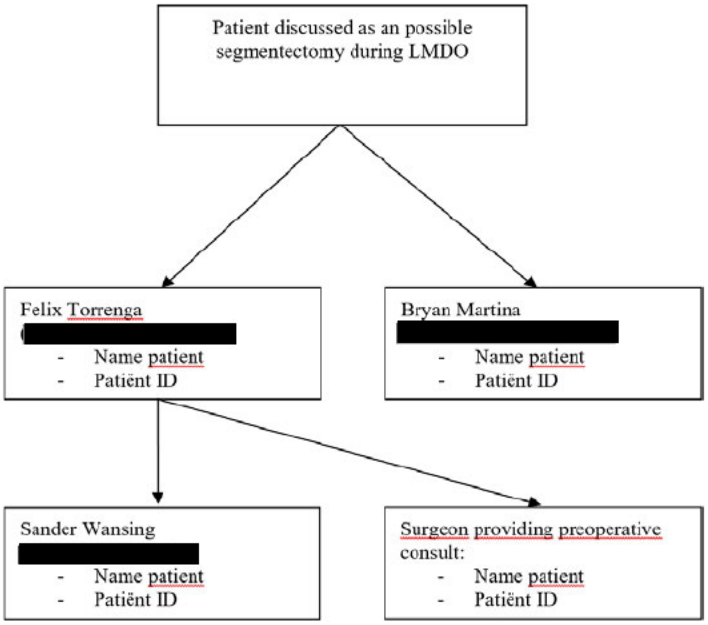

Figure 7:Workflow preoperative communication.

2.3.3.Participants

Patients with stage 1A NSCLC who were discussed as potential candidates for segmentectomy at the LMDO between 01-03-2024 to 26-07-2024 were included. If a patient with stage 1A NSCLC was discussed for stereotactic radiotherapy or if no contrast-enhanced CT was available, then this patient was not included. Patients were excluded from this study if no or a different operation was performed.

2.3.4.Bias

No bias is expected, this is primarily an observational study.

2.3.5.Study size

The study size was determined by the number of segmentectomies in the period from 01-03-2024 to 26-07-2024.

2.3.6.Statistical methods

As a low number of participants is expected due to the low volume of segmentectomies at the MST, the analysis will consist of descriptive statistics only.

3. Results

3.1. A comparative evaluation of manual segmentation methods for the preoperative visualisation of the pulmonary structures for segmentectomies

3.1.1.Participants

A total of 50 patients received contrast-enhanced thorax CT scans in February of 2024. Out of these patients, 31 were excluded based on the criteria in Table 1. 8 patients were excluded due to moderate-severe atelectasis (n=8), pulmonary effusion (n=8), and pulmonary fibrosis (n=8). One patient was excluded due to insufficient contrast in the pulmonary artery. Furthermore, 4 patients were excluded due to the CT having severe movement artefacts, one patient was excluded due to malpositioning, one patient was excluded due to a large mediastinal abscess, and one patient was excluded due to extensive tumours in both lungs. Of the remaining 19 patients, 16 were chosen randomly and used for this study. These patients were divided into the right or the left group, determining which lung of the patients would be modelled as if a tumour resided there. An overview of the selection process can be seen in Figure 8.

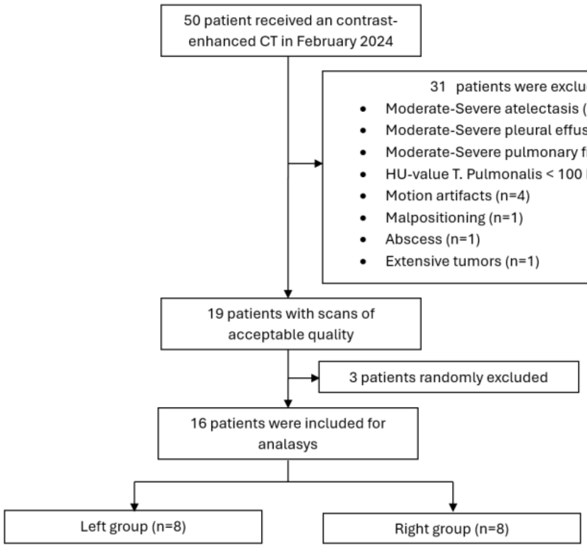

Figure 8: Patient inclusion flowchart software analysis.

The included patients consisted of 6 women and 10 men. The median age was 65 years, and the median BMI was 27 kg/m^2. Only one patient had prior thoracic surgery. 4 patients had comorbidities, two of which were COPD GOLD II. Two patients had pulmonary fibrosis of the right upper lobe. One patient had an elevated left diaphragm. In one patient, several infectious abnormalities were found. One patient had small consolidations and an abscess in the left lower lobe, this patient was incidentally placed in the right group so these abnormalities did not interfere with the segmentation process. Three patients showed abnormalities on the CT scan that could be of oncological origin. One patient had micro nodes in the left upper lobe, one patient had small ground-glass opacities in the left lower lobe, right upper lobe and right lower lobe. In the last patient, a 4mm suspicious nodus was found in the right middle lobe. A description of the study population can be seen in Table 2, and a full overview of the characteristics of the patients included in this study can be found in Appendix E.

[redacted]

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[redacted]

[redacted]

[redacted]

[redacted]

3.1.2.Results of [redacted]

[redacted]

[redacted]

Visually the models look similar. It can be noted, however, that the standard visualisation of the [redacted]

[redacted]

[redacted]

[redacted]

Figure 10: Clustered boxplots; Top left: [redacted]

Table 4: Results of [redacted]

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]

Table 5: Results of the [redacted]

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
			[redacted]	[redacted]		
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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*Significant P-values calculated with Friedmann's test were corrected using the Holm-Bonferroni method (factor = 8).

3.2. Tree-dimensional modelling as a tool for preoperative planning of VATS Segmentectomies for patients with 1A NSCLC

3.2.1.Study Population

During the most recent inclusion period (01-12-2023 until 26-07-2024) 12 patients have been included in the study. Of the 12 patients, 11 were male, and one was female. Five patients received a lobectomy. One patient underwent a lobectomy due to a segment resection not being technically achievable. One patient had a lingula-sparing lobectomy, where segments S1, S2, and S3 are removed leaving S4 and S5 in the left upper lobe. Patient 3 had a lesion that was initially deemed respectable, but via biopsy, the lesion was identified to be non-cardiogenic resulting in an observational approach. One patient was planned for segmentectomy, but due to rapid decline received stereotactic radiation therapy. One patient with poor pulmonary function received a wedge resection due to a segmentectomy not resulting in ontologically satisfactory margins.

In addition to this group, seven patients who underwent segmentectomies in 2023 were identified. Three patients were excluded because no contrast scan was available. Two patients were excluded because the contrast images were only available in 3 mm slices.

Combined, a total of 14 patients were included in the study. The patients had a median age of 65 [60 - 72] years and a median BMI of 25 [22 - 29]. Preoperative lung function tests revealed that the median predicted forced expiratory volume in 1 second (FEV1) was 77% [61 - 105] and the median diffusion capacity of the lung for carbon monoxide by single breath (DLCO

SB) was 71% [58 - 84]. A complete overview of the patients can be found in Table 6.

3.2.2. Change of surgical plan

The answers given to the change of plan forms are visible in Appendix G. In [redacted] instances the surgeon made a critical alteration of the surgical procedure. This resulted in a change of plan of [redacted]

[redacted].

3.2.3. Quality of the model

The models were scored highly on the rubric questionnaire in Appendix D. [redacted]

[redacted]

Table 6: Patient characteristics

Name	Age	Sex (m/f)	Size tumour (mm)	Scan protocol	Slice thickness (mm)	Spacing between slices (mm)	Pixel spacing (mm)	Tumour location (lobe)	Clinical TNM8 (preoperative)	Comorbidities	smoking history (pack years)	ASA	BMI (kg/m^2)	FEV 1(%)	DLCO SB (%)
TC-01 (1)	61	M	19	CTA Pulmonalis	1	0.8	0.7578	LUL	cT1bN0M0, 1A2	NR	19	3	28.06	69	76.8
TC-02 (2)	60	M	9	CTA Pulmonalis	1	0.8	0.8047	RLL	cT1bN0M0, 1A2	NR	36	3	32.55	84	86.4
TC-03 (3)	76	M	13	Thorax Abdomen IVC	1	0.8	0.7539	RLL	cT1bN0M0, 1A2	NR	11	2	24.86	116	NR
TC-04 (4)	55	F	13	CTA Pulmonalis	1	0.8	0.7031	RUL	cT1aN0M0, 1A1	NR	never smoked	3	34.68	76	120
TC-05 (5)	76	M	13	CTA Pulmonalis	1	0.8	0.6543	LUL	cT1bN0M0	COPD GOLD III, diffusion-disorder	53	NR	19.72	45	50
TC-06 (6)	67	M	13	Thorax BB	1	0.8	0.8184	RLL	cT1cN0M0, 1A3	COPD GOLD II + mild diffusion disorder	8	3	31.14	63	72.5
TC-07 (7)	59	M	16	CTA Pulmonalis	1	0.8	0.6914	LLL	cT1bN0M0, 1A2	NR	22	NR	21.59	116	69.2
TCT-01 (8)	70	M	No tumour	FDG PET Whole Body	0.977	0.9766	0.9766	RUL	cTxN0N0	NR	never smoked	2	26.12	99	76
TCT-02 (9)	71	M	18	CTA Pulmonalis	1	0.8	0.7578	RUL	cT1bN0M0, 1A2	Pulmonary embolism, asthma	12	3	25.71	101	NR
TCT-03 (10)	74	M	13	Thorax Abdomen IVC	1	0.8	0.7482	RUL	cT1bN0M0, 1A2	COPD GOLD II	16	3	20.61	78	87.5
TCT-04 (11)	63	M	16	Thorax BB	1	0.8	0.7715	RLL	cT1bN0M0, 1A2	COPD GOLD III/IV	100	3	27.32	43	52.2
TCT-05 (12)	70	M	9	Thorax	1	0.8	0.7598	RUL	cT1aN0M0, 1A1	COPD GOLD II	54	3	24.76	56	60.1
TCT-06 (13)	60	M	16	Thorax BB	1	0.8	0.7461	LLL	cT1bN0M0, 1A2	-	22	NR	21.59	116	69.2
TCT-07 (14)	60	M	11	Thorax	1	0.8	0.748	RUL	cT1bN0M0, IA2	COPD GOLD II , emphysema, mild diffusion disorder	44	NR	22.22	74	57

ASA, American Society of Anaesthesiologists; BMI, body mass index; FEV1, forced expiratory volume in 1 second; DLCO SB, diffusion capacity of the lung for carbon monoxide by single breath; TNM 8, Tumour Node Metastasis classification 8th edition; LUL, left upper lobe; RLL right lower lobe; RUL, right upper lobe; LLL, left lower lobe; COPD, chronic obstructive pulmonary disease; GOLD, Global Initiative for Chronic Obstructive Lung Disease.

3.3. Prospective evaluation of 3D models for VATS segmentectomies

3.3.1. Study Population

A total of 7 patients with stage 1A NSCLC were discussed as candidates for a potential segmentectomy at the LMDO during the inclusion period. Of these 7 patients, 4 patients were excluded. 2 patients were excluded due to receiving a lobectomy. 1 patient was excluded due to receiving a wedge resection, and 1 patient was excluded due to receiving stereotactic radiation therapy. The remaining three patients underwent segmentectomy. An overview of these patients can be found in Table 7.

3.3.2. Intraoperative images

All segmentectomies were performed with the use of VATS. Images were collected and relevant anatomical structures were matched to the 3D model to assess the accuracy of the model for the intraoperative guidance of segmentectomies. An overview of these structures can be seen in Table 8.

Table 8: Target structures on the 3D model and structures visualised during surgery.

Patient nr.	Target structures	Structures identified during surgery
1	A2, V1+2, B2	A2, V1+2, B2
2	A6, B6	A6, B6
3	V2b, V2c, A2b, A2c, B2	V2b, V2c, A2b, A2c, B2

3.3.2.1. Patient Case 1

Patient 1 was included in the study after a 9 mm Fluorodeoxyglucose (FDG)-Positron Emission tomography (PET)- avid lesion in the right upper lobe. A 3D model of the pulmonary structures was made using a Thorax Abdomen CT scan with intravenous contrast. The preoperative plan was primarily based on the 3D model in Figure 12 and consisted of a segmentectomy of segment 2 and an additional wedge resection of segment 3.

[redacted]

Preoperative planning indicated 2 structures to be targeted: the artery to segment 2 (A2), and the bronchi to segment 2 (B2). The remaining structures, including the veins leading, were to be separated with a stapler after ICG administration. The 3D model helped the surgeon to [redacted]

Table 7: patient characteristics prospective use of 3D models

Patient Nr.	1	2	3
Age	74	60	60
Sex (m/f)	M	M	M
Size tumour (mm)	13	16	11
Scan protocol	Thorax Abdomen IVC	Thorax BB	Thorax IVC
Slice thickness (mm)	1	1	1
Spacing between slices (mm)	0.8	0.8	0.8
Pixel spacing (mm)	0.7482	0.7461	0.748
Tumour location (lobe)	RUL	LLL	RUL
Clinical TNM8 (preoperative)	T1bN0M0, 1A2	T1bN0M0, 1A2	T1bN0M0, IA2
Comorbidities	COPD GOLD II	-	COPD GOLD II, emphysema, diffusion disorder
smoking history (pack years)	16	22	44
ASA	3	NR	NR
BMI (kg/m^2)	20.61	21.59	22.22
FEV1(%)	78	116	74
DLCO SB (%)	87.5	69.2	57
Pathological TNM8	pT1aN0PL0, 1A1	pT1bN0PL0, 1A2	pT1bN0M0, 1A2

IVC, intravenous contrast; BB, abdomen; RUL, right upper lobe; LLL, left lower lobe; TNM 8, Tumour Node Metastasis classification 8th edition; COPD, chronic obstructive pulmonary disease; GOLD, Global Initiative for Chronic Obstructive Lung Disease; ASA, American Society of Anaesthesiologists; BMI, body mass index; FEV1, forced expiratory volume in 1 second; DLCO SB, diffusion capacity of the lung for carbon monoxide by single breath;

[redacted]

3.3.2.2. Patient Case 2

Patient 2 was introduced with a 16 mm FDG-PET-avid lesion in segment 6 of the left lower lobe. A 3D model was created with a CT scan with intravenous contrast of the thorax and upper abdominal region. The preoperative plan was primarily based on both the CT combined with the 3D model in Figure 14 as the lesion was close to the fissure and the surgeons were unsure if it interacted with the adjacent left upper lobe.

[redacted]

The preoperative panning allowed the surgeons to [redacted]

[redacted]

3.3.2.3. Patient Case 3

Patient 3 was discussed at the LMDO presenting with an 11 mm FDG-PET-avid lesion in the right upper lobe. A 3D model was created using a thorax CT scan with intravenous contrast. The preoperative plan was primarily based on the 3D model in Figure 16. The preoperative plan consisted of a segmentectomy of segment 2 with a wedge of segment 1.

[redacted]

The arterial supply of segment 2 was made up of 3 separate arterial branches: A2a, A2b, and A2c. with only A2b and A2c being visible after dissecting the fissure. The veinous drainage was provided by 3 separate veins: V2a, V2b and V2c, with V2a coming from a common vein that splits peripherally to V2a and V1b. The 3D visualisation allowed the surgeons to [redacted]

[redacted]

4. Discussion

4.1. Software comparison

In this thesis, a new segmentation workflow for the visualisation of the segmental bronchi, arteries, and veins was developed for [redacted] This new segmentation method was compared to [redacted]

[redacted]

[redacted]

[redacted]

The graphs show that the [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Currently, it is unknown how exactly the [redacted]

[redacted]

[redacted]

4.1.1.3. Lobe segmentation

The lobes generated by [redacted]

[redacted]

4.1.1.4. General

The 3D models were only compared against one another. In literature, the golden standard for a model of the airway is a manually segmented model that has been validated by at least 2 experienced radiologists (31). This was however not possible due to the labour and time needed for production. Another accepted dataset for reference segmentation is that of the EXACT 09 study. To get access to this dataset an automatic algorithm must be tested which is not covered in this research (32).

The [redacted] software programs were tested sequentially. All models were produced using [redacted].

When making a 3D model in either program, [redacted]

4.2. Quality of the model

In this part of the study, a total of 14 patients were modelled using the [redacted] protocol. [redacted]

All models, except the model of patient 2 were deemed usable for the preoperative planning of segmentectomies. This suggests that the current protocol for preoperative 3D modelling does not need to be limited to only late-phase contrast CT scans but can be used on a large range of CT with intravenous contrast. These scans are readily available for the patient group, as it is hospital policy to have at least one thin-slice preoperative scan with CT. The ability to also produce sufficient-quality models using the raw CT images from FDG-PET scans only adds to the versatility.

Here, one of the surgeons rated [redacted]

[redacted]

Regarding this patient, surgeon 2 felt [redacted]

4.3. Change of plan

The change of plan reported in this study was [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

4.4. Preoperative planning in practice

During this study, preoperative 3D planning was applied to 3 patients who underwent a segmentectomy. Before this was possible, informed consent was gathered as per the protocol of the non-Medical Research Involving Human Subjects Act (nWMO) study of the 3D lab. Interoperative images were collected to compare the visible local anatomy with the bronchi, arteries, and veins that were earmarked as targets during segmentectomy using 3D visualisation. All relevant arteries, veins, and bronchi were visualised during surgery. Of all these structures, only A2c was not litigated. This was by choice, and not due to any uncertainty about the classification of the artery. A summary of these structures can be seen in Table 8.

The fact that all relevant structures were visualised during surgery and had the right location compared to one another indicates that these models can be relied upon to make interoperative decisions. In each of these cases, the 3D model added a degree of certainty for the operator. The models allowed the surgeons to check perioperatively what structures they were looking at and identify those that needed to be isolated.

In patient 1, the 3D model showed that the right upper lobe was only supplied by a single A2 (in contrast to patient 3) and that it drained in a common trunk of a vein supplying both segments 1 and 2. This made the surgeons decide to [redacted]

In patient 2, the surgeons were able to determine that S6 only had one common artery, ruling out anatomical variants where A6 originates from 2 (24%) or 3 (2%) different stems(33). This made the operation much simpler compared to having to search for additional arteries present in these variations.

Patient 3 had a right upper lobe with a complicated vascular pattern. Segment 2 was supplied by 3 individual arteries, and 2 individual veins, sharing an additional common vein with segment 3. With the 3D model, the surgeons were able to [redacted]

To more accurately determine the clinical relevance of these models in the future, the surgeon can be asked to [redacted]

The limited sample size of this study restricts the analysis of clinical outcomes such as blood loss, operation time, and resection margin. A recent meta-analysis concluded that perioperative 3D visualisation could decrease intraoperative blood loss, operative time, postoperative hospital stay, the total number of complications, and conversion rate (from segmentectomy to lobectomy or thoracotomy) compared to non-3D procedures (34). A more recent study also indicates that the use of a 3D model might also facilitate shorter operating times, a reduction in intraoperative blood loss, fewer incisions and a shorter length of stay(35). There is limited data on the long-term effects of the use of preoperative 3D visualisation for segmentectomies.

4.5. General discussion and future recommendations

An important aspect of a new application of 3D visualisation is how it can be applied within the workflow. In section 2.3.2 a workflow is introduced for this research. This workflow requires the researcher to be present at the LMDO, make an appointment to get the most recent CT scan with intravenous contrast at the radiology, and be present at the preoperative consult to get informed consent as per the nWMO of the 3D lab. If preoperative 3D visualisation becomes part of the preoperative workup of the patient, the model should be requested by the surgeon present at the LMDO if a segmentectomy is indicated. When looking at the change of plan study, a segmentectomy was chosen [redacted] times based on CT. Only [redacted] was a segmentectomy change to a Lobectomy after reviewing the 3D model. This implies that, if the 3D model is requested when a patient is deemed a candidate for segmentectomy based on CT and clinical status, he will probably be planned for a segmentectomy, albeit with different target segment(s).

The model should be produced by a technical physician well acquainted with pulmonary anatomy. To eliminate the need for preoperative informed consent, a risk analysis could be performed in collaboration with the 3D lab. As a preoperative 3D visualisation is a class 1 medical device, and the surgeons could always fall back on conventional 2D scans, the risk is deemed low. Currently, [redacted] software must be installed on a device to present the model to the surgeon. This might prove to be a logistical challenge, as this software cannot be installed on the computers of the hospital network. The online platform from [redacted] [redacted] [redacted] can be used to view a segmentation on a computer without additional software being installed. The technical physician can upload the segmented model, and the surgeon can view the model at any time thus removing the need for a dedicated software program and making the model accessible at all times.

[redacted]

In addition to software programs with which you can produce the model via manual segmentation, numerous companies offer the segmentation of the pulmonary bronchi, veins, and arteries for segmentectomies. The most well-known software package using AI-mediated segmentation is PulmoVR, developed by MedicalVR (Nijmegen, The Netherlands). PulmoVR utilizes LungQ software (Thirona, Nijmegen, The Netherlands) to segment the segmental arteries, veins, and bronchi, and simulate the ISP by dividing the lung parenchyma into different segments. One major advantage of AI-mediated segmentation is that these segmentation methods work with non-contrast-enhanced CT scans allowing for a wider range of scans that can be used for 3D modelling. (22).

More recently, [redacted] launched [redacted]

When comparing the current model to commercial solutions, the main disadvantages are that a contrast-enhanced CT is necessary to model the pulmonary vessels, the model must be produced by an operator well versed in both 3D modelling and the pulmonary anatomy the time it takes to make a model, and the inability to simulate the intersegmental plane. The proposed method no longer necessitates the transfer of patient data to an external entity, and is most likely cheaper, as the model can be made within an hour with one of the [redacted] licenses available via cooperation with the [redacted] [redacted] [redacted]. Since the segmentation is done in-house, the models can be produced on a more flexible schedule.

5. Conclusion

To conclude, the new segmentation method using the [redacted] produces adequate models for preoperative visualisation of the pulmonary segmental anatomy for patients with NSCLC. Compared to the already developed segmentation protocol at [redacted] [redacted] the new segmentation method is equally time-efficient and might have an edge over this protocol when it comes to the segmentation of the airway. The preoperative 3D models lead to a significant change of plan and increase the understanding of the surgeon of the patient-specific anatomy potentially leading to more accurate and safer segmentectomies in the future.

“During the preparation of this work, I used ChatGPT to make suggestions for the structuring of paragraphs. After using this tool/service, we thoroughly reviewed and edited the content as needed, taking full responsibility for the final outcome. No content was directly taken from the ChatGPT outputs.”

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