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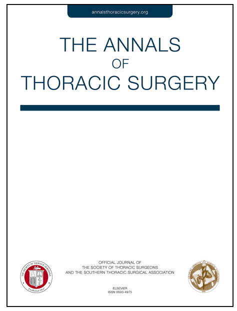

Operative planning in Thoracic Surgery: A pilot study comparing imaging techniques and 3D printing

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Operative planning in Thoracic Surgery:

A pilot study comparing imaging techniques and 3D printing

Running Head: Imaging techniques and 3D printing

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ABSTRACT (Word Count: 246)

Background:

Careful preoperative planning in thoracic surgery is essential for positive outcomes especially in video assisted thoracic surgery (VATS) where palpation and 3-dimensional imaging is restricted.

The objective of this study was to evaluate the ability of different imaging techniques such as Computerized Tomography (CT) scanning, maximal intensity projection (MIP) imaging, 3-dimensional (3D) reconstruction as well as 3D printing, to define the anatomy of the hilar structures prior to anatomical lung resection.

Methods:

All patients undergoing elective lung resections by VATS for cancer under a single surgeon were identified over a three-month period. A single surgeon was asked to record the number of pulmonary artery branches supplying the lobe to be resected using the preoperative CT scan, MIP images and 3D reconstructed CT images. 3 patients had their lung hilum printed. These were then compared to the intraoperative findings.

Results:

16 patients had their preoperative imaging analyzed. A further 3 patients had their lung hilum 3D printed. Although not statistically significant, the 3D prints of the hilum were found to be the most accurate measurement with a correlation of 0.92. CT, 3D reconstructed CT and MIP images tended to under recognize the number of arterial branches and therefore scored between 0.26 and 0.39 in terms of absolute agreement with the number of arteries found at operation.

Conclusions:

3D printing in the planning of thoracic surgery may suggest a benefit over contemporary available imaging modalities and the use of 3D printing in practicing operations is being established.

Careful preoperative planning using pulmonary imaging techniques in thoracic surgery is essential for positive outcomes [1-3]. This is especially true in anatomical lung resection where care has to be taken to avoid injury to the highly vascular hilar structures. Twenty to thirty per cent of patients can present with variable numbers of arterial and venous branches [3-4]. Preoperative imaging of the hilar structures to recognize their position, orientation and relationship with one another will help the surgeon safely dissect and divide the structures during surgery. This is especially important in video assisted thoracic surgery (VATS), where palpation and 3-dimensional view is restricted, with reported vascular injuries occurring in around 2.9% of cases requiring conversion to open surgery in around 2.2% [5].

Multi-detector computed tomography (MDCT) is now the main imaging technique for preoperative imaging of the thorax. This modality has developed significantly in recent times reducing both the time required to perform a study as well as the amount of radiation the patient receives [5]. The speed of the study helps reduce motion artefact from the patient's respiration [6]. Dual-source computerized tomography (DSCT) uses two cathode ray tubes to further reduce time and artefact [7]. Image quality and resolution is then enhanced using contrast [8]. Although this is helpful in delineating the number and relative positions of the vessels and bronchi, mentally translating 2D images from a CT acquisition into a three-dimensional (3D) conceptualization can be problematic [9].

In recent years, post processing tools that use the data produced from the CT scan to produce further images have been developed that may enhance the surgeon's ability to delineate the relevant surgical anatomy.

MIP

Maximum intensity projection (Maxi, or MIP) is an image reconstruction method that increases the conspicuity of structures of high attenuation- for example, pulmonary vessels- and so allows such branching structures to be optimally illustrated on a 2D image. This technique has been used to make identification of pulmonary nodules and emboli more reliable [10-11].

Volume rendering

Volume rendering (VR) is an easily performed, automated reconstruction technique whereby CT attenuation values are mapped to opacity, brightness, and color. This produces a 3D depiction of structures of different density. Additional techniques called clip planes and clip boxes can be used to scroll through the volume-rendered dataset. In this way, the surgeon is able to “drill” through the image to selectively conceal or reveal anatomical structures of interest, gaining depth perception of the hilar structures and identifying the trajectory of branching vessels. This enhanced anatomical understanding is integral to planning the steps of the operation [12-13].

3D printing

3D printing has now become a popular emerging technique used in various branches of medicine and surgery. It has been used to help preoperative planning in these specialties allowing surgeons to carry out in vitro surgeries in preparation for the surgery such as in thoracic surgery by printing hilar structures and using these to plan VATS lung resections to a degree of success [14]. These models of anatomical structures have allowed surgeons to plan operations with higher perceived accuracy. In some cases, the 3D models have actually changed the surgical strategy [15]. Using these 3D prints, simulators have been developed to enable surgeons to simulate the operation as a form of practice, thereby theoretically reducing the risk to the patient [16-17].

Objective

The objective of this study was to evaluate the ability of these imaging techniques: CT scan, MIP imaging, volume rendering and 3D printing, to define the anatomy of the hilar structures prior to anatomical lung resection.

PATIENTS AND METHODS

Approval for the study from the joint research and enterprise office was obtained and the requirement for consent was waived. Data was collected prospectively. All patients undergoing elective lung resections by VATS for cancer under a single surgeon were identified over a three-month period. Patients undergoing lower lobe resections were excluded from the study as were patients undergoing any sub-lobar resections.

All patients underwent a preoperative CT scan the day before surgery. CT scanning was performed using a Phillips CT scanner at 100-120 kept and 80–229 mA tube current (varying according to patient weight), with helical acquisition, the patient supine, and a total scanning time of 500 seconds. All scans were acquired after a delay of approximately 30 seconds following IV administration of a 100ml bolus of iodinated contrast (Omnipaque 300). The acquired contrast enhanced CT (CECT) scans were of 2.00mm, 1.25mm and 1.00mm reconstructed slice thicknesses and anonymized. Axial CT datasets were viewed using Centricity PACS software (GE Healthcare LTD, USA). MIP images and 3D reconstruction were created using the MM Reading workflow on the Synovia platform (Siemens, Forcheim, Germany) (Figure 1). MIP images were standardized to 10mm thickness with a 1mm increment, but manipulation of thickness was permitted to optimize visualization (Figure 2). Volume rendered images were visualized using the Clip Plane and Clip Box functions (Figure 3). Where necessary, for both MIP and volume rendered images the planes of viewing were adjusted to obtain oblique (i.e. non-orthogonal) views of the thorax to optimally visualize vessels.

Each reconstruction (axial, MIP and VR) was then analyzed for 5 minutes by a single cardiothoracic registrar. This was to reflect a feasible alteration to real-world practice and ensure no imaging modality was advantaged by extended analysis. For each patient and reconstruction method it was noted how many branches of the pulmonary artery there were to the lobe that was to be removed at operation. The registrar using the software had been trained in its use by a consultant radiologist for two hours prior to starting the study. They were also blinded to the demographics and were not involved in the operation. The CT images, MIP images and 3D reconstructions were analyzed at separate occasions to limit recall bias.

During the operation of each patient, the consultant surgeon recorded how many branches of the pulmonary artery there were to the lobe being resected in the operation note. This finding was then compared to the results from the preoperative imaging modalities.

Three patients had their CT scans segmented using ITKSnap 3.6.0[18]. The entire pulmonary artery, vein and bronchial tree of the lung were segmented. The 3D printer readable data files that were produced were then used to produce a 3D print. The 3D printer used was the 2040 WASP delta turbo, using fused deposition modelling as the printing technology. The 1.25mm slice thickness CT was printed using 340-20000 P400-P ABS filament cartridge (white) material; the 2.00mmand 1.00mm slice thickness CTs were printed with the ABSplus-P430 material (yellow). Immediately following printing, the printed components were submerged in a Thermo-Scientific incubator containing an alkaline solution at 60 degrees centigrade for 8 hours, to remove the support material from the components. Pliers were then used to remove any remaining support material. The models were then analyzed and the number of pulmonary artery branches to the lobe being resected was recorded (Figure 4).

STATISTICAL ANALYSIS

Statistical analysis was performed using SPSS 19.0 (SPSS Inc., Chicago, IL, USA). Statistical analysis included the test for normality and the intra-class correlation test to measure both agreement and consistency with the results against the actual number of arterial branches found at operation. A p value of < 0.05 was considered statistically significant.

RESULTS

The number of patients undergoing upper or middle lobectomies during this time was 16 (n = 16). The average age of the patients was 69 (53 – 82). There were 3 male patients and 13 female patients. All patients had complete datasets for number of pulmonary artery branches found on CT scanning, 3D reconstruction, MIP images and at operation. 2 patients underwent right VATS and middle lobectomies, 5 patients underwent left VATS and upper lobectomies and 9 patients underwent right VATS and upper lobectomies. Conversion rate was zero, and no major intraoperative blood loss was recorded. 3 patients had their CT scans segmented and a 3D print made of their lung hilum.

The number of arteries found on the different imaging modalities including the 3D prints as well as at operation are summarized in table 1.

Tables 2 and 3 summarize the intra-class correlation between the findings using each imaging modality and the findings at the time of operation. Although not statistically significant, the 3D prints of the hilum were found to be the most accurate measurement with a correlation of 0.92. CT, 3D reconstructed CT and MIP images tended to under recognize the number of arterial branches and therefore scored between 0.26 and 0.39 in terms of absolute agreement with the number of arteries found at operation. However, this result was not statistically significant.

COMMENT

This study reviews the preoperative imaging options available to the current thoracic surgeon and highlights the danger of relying too heavily on these images in accurately assessing the branches of the hilar structures. It also highlights the development of 3D printing and its use in thoracic surgery as a surgical strategy planning tool when undertaking anatomical lung resections.

It is presumed that preoperative knowledge of the hilar relationships allow for safer dissection of the hilum in lung resections. However, it is difficult to objectively measure the surgeon's knowledge of the structural relationships and therefore we have used the number of arterial branches as a surrogate marker of this. The authors believe that the ability to use these imaging techniques to accurately define the number of pulmonary arterial branches also allows the surgeon to accurately assess other aspects of the anatomy.

On reviewing the anatomy using the differing imaging modalities there were clear benefits and drawbacks of each. Axial thin-section CT reconstructions are readily available without any need for post-processing of the data acquired and surgeons are well rehearsed in interpreting them as the routine preoperative imaging. Such datasets demonstrate the fissure well and therefore it is easy to appreciate the boundaries of the lobe. It is difficult to appreciate the 3D aspect of the lung hilum, and although this will improve with experience, it is therefore harder to define the relationships and trajectories of the hilar structures. It is often difficult to delineate between venous structures and arterial structures depending on the exact phase of contrast injection.

MIP reconstructions significantly enhanced the fissure compared to axial datasets. It was also qualitatively much easier to identify the pulmonary artery branches even though there was no significant advantage over CT alone found in this study. It was easier to delineate the venous and arterial branches than CECT alone. The MIP images still required the viewer to scroll through the slices and gave little benefit over CT in recognizing the 3D anatomy.

3D reconstruction of the hilum was much more useful in appreciating the angles and relationships of the hilar structures then both CT and the MIP images. The 3D reconstructions can be manipulated to be viewed from the angle a thorascope would view the hilum and the angles required for safe dissection and division appreciated. Relationships to the chest wall can be defined and preoperative planning of VATS ports and incisions can be made. 3D reconstruction did not allow for fissure recognition and the fissure was lost in processing the CT data. It is therefore more difficult to define the boundaries of the lobe and which vascular structures are related to it.

CT, MIP and volume rendering imaging techniques underestimated the number of arteries found at operation. This was thought to reflect the limit imposed by the maximal image resolution. It was therefore both more difficult to appreciate a vessel branch as well as identify a branch as two individual branches as opposed to one single branch. At the time of operation however the smaller branches and multiple branches were more easily appreciated.

It could be argued that MIP and volume rendered reconstructions required the user to produce the images using software and workstations, and is therefore likely to be both user-dependent and limited in scope. However, modern picture archiving and communications systems (PACS), universally used for the viewing of all digital imaging, increasingly incorporate the ability to reconstruct MIPS and volume rendered images on any PC, thus bringing these imaging techniques increasingly into the mainstream.

It was not feasible to include sub-lobar resections in this study. This was due to the difficulty of consistently defining the anatomical boundaries of specific segments and the overlap these have with non-anatomical wedge resections. The exclusion of the lower lobe lung resections was due to the surgical technique often employed that results in dividing the artery in the fissure of the lung, and therefore not individually dividing and counting the actual branches of the artery after it passes the fissure. There is also less variability seen with the arterial anatomy in the lower lobe.

The main benefit of 3D printing is the ability to produce patient specific anatomy in a way that is easy to spatially recognize and therefore making it easier to plan operations. The novel segmentation pathway that was used in this study enabled the DICOM files produced from the CECT to be converted to 3D printable files in around 10 minutes.

The cost of 3D printing is often viewed as a limiting factor; however, the production of single prints is similar to the cost of single stapler reload used in thoracic surgery and in the region of one to two hundred pounds. The financial burden lies in the cost of the printer itself, however major centers often have access to a 3D printer. As 3D printing becomes more ubiquitous, economies of scale will arguably also diminish its financial disadvantage. It may be that the financial and resource requirements of using this technology is reserved for the most complex procedures that will most likely benefit the most from extended pre-operative planning.

The range of materials available for use in 3D printing of the lung hilum allows the models to replicate tissue properties. These models can therefore form the working parts of patient specific simulators. This would allow the surgeon to practice the actual operation in a high-fidelity simulator in a no risk environment.

LIMITATIONS OF THE STUDY

Due to the small sample size the results for this study failed to meet the level required to be deemed statistically significant. Furthermore, only a single surgeon reviewed the imaging studies and therefore it is not possible to conclude that these findings would be reproduced by all surgeons.

CONCLUSIONS

CT scanning remains the mainstay of conventional preoperative imaging. However, 3D printing in the planning of thoracic surgery may suggest a benefit over contemporary available imaging modalities. Furthermore, the use of 3D printing in practicing operations is being established and the development of simulator models using patient specific anatomy is well underway. Further prospective studies to analyze the impact on surgical outcomes and the cost of 3D printing and post-processing techniques are needed to evaluate the cost effectiveness of this technology.

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TABLES

Table 1: Number of arteries seen on CT, 3D reconstruction, MIP, intra-operatively and after 3D printing.

Patient	CT arteries	CT 3D arteries	MIP arteries	Actual arteries	3D print arteries
1	3	3	4	**4**	4
2	3	3	3	**6**	6
3	3	3	3	**4**	5
4	2	1	2	**4**	
5	2	3	4	**4**	
6	3	1	3	**5**	
7	2	2	2	**4**	
8	1	3	3	**3**	
9	2	1	2	**2**	
10	1	0	0	**2**	
11	2	2	2	**3**	
12	1	2	2	**3**	
13	2	2	2	**2**	
14	2	2	2	**3**	
15	2	2	2	**2**	
16	2	2	2	**7**	

Table 2: Comparison of consistency between CT, CT 3D, MIP and 3D printing with intra-operative findings.

Consistency	CT	CT 3D	MIP	3D print
Correlation	0.55	0.43	0.53	0.92
LCL	-0.28	-0.63	-0.34	-2.00
UCL	0.84	0.80	0.84	1.00
F Test	2.23	1.76	2.14	13.0
df1	15	15	15	2
df2	15	15	15	2
p	**0.066**	**0.143**	**0.076**	**0.071**

LCL – lower confidence limit; UCL – upper confidence limit; df – Degrees of Freedom

Table 3: Comparison of agreement between CT, CT 3D, MIP and 3D printing with intra-operative findings.

Agreement	CT	CT 3D	MIP	3D print
Correlation	0.33	0.26	0.39	0.92
LCL	-0.27	-0.29	-0.29	-0.24
UCL	0.72	0.67	0.76	1.00
F Test	2.23	1.76	2.14	13.0
df1	15	15	15	2
df2	15	15	15	2
p	**0.066**	**0.143**	**0.076**	**0.071**

LCL – lower confidence limit; UCL – upper confidence limit; df – Degrees of Freedom

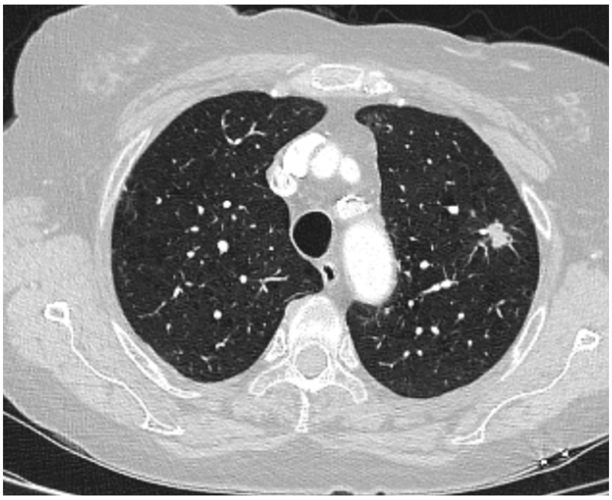
FIGURE LEGENDS

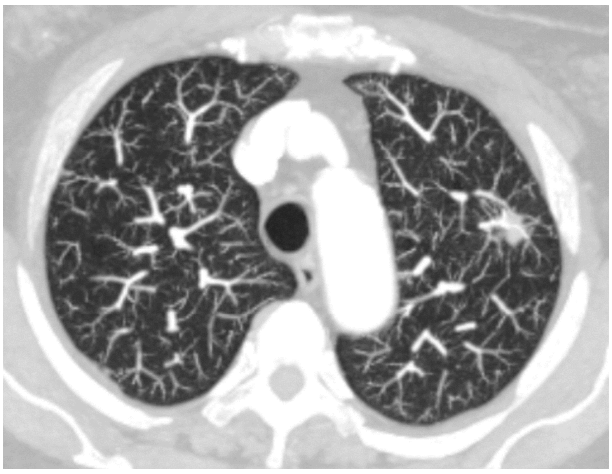
Fig 1: An axial CT image of a left upper lobe of lung containing a lung tumor.

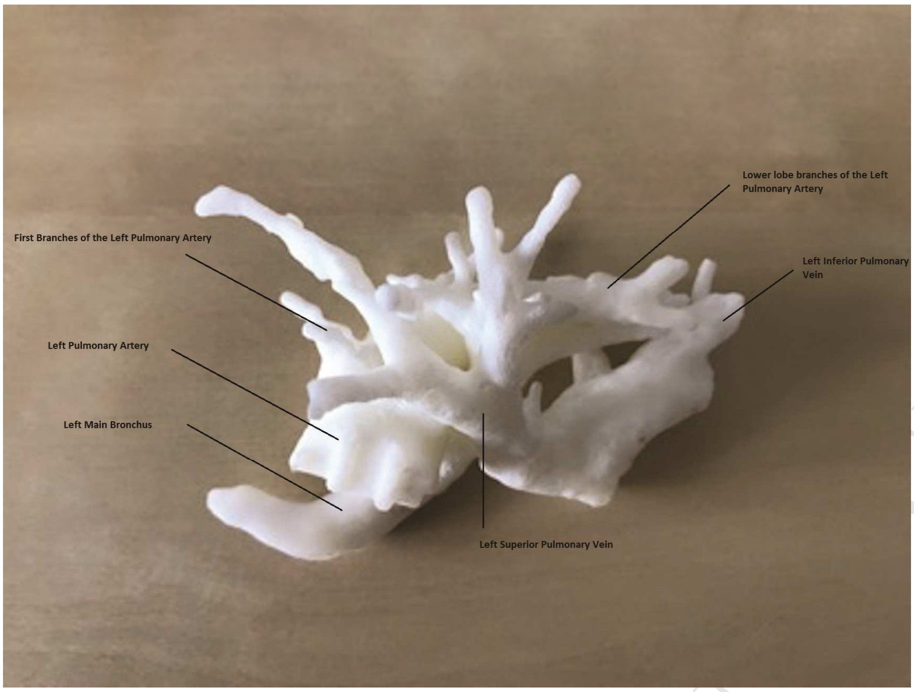
Fig 2: An axial MIP image of a left upper lobe of lung containing a lung tumor.

Fig 3: A volume rendered 3D reconstruction of a left upper lobe of lung containing a lung tumor.

Fig 4: 3D printed left lung hilum of a patient who underwent a left VATS and upper lobectomy.







First Branches of the Left Pulmonary Artery
Left Pulmonary Artery
Left Main Bronchus
Lower lobe branches of the Left Pulmonary Artery
Left Inferior Pulmonary Vein
Left Superior Pulmonary Vein