Surgical Technique

Planning and marking for thoracoscopic anatomical segmentectomies

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Abstract: Although sublobar resection (SLR) for treating non-small cell lung carcinoma (NSCLC) is still controversial, thoracoscopic segmentectomy is rising. Performing it by closed chest surgery is complex as it means confirming the location of the lesion, identifying vascular and bronchial structures, preserving venous drainage of adjacent segments, severing the intersegmental plane and ensuring an oncological safety margin with no manual palpation and different landmarks. Accurate planning is mandatory. We discuss in this article the interest of 3D reconstruction and mapping technics to enhance safety and reliability of these procedures.

Keywords: Thoracoscopic surgery; lung cancer; segmentectomy; lung reconstruction

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Introduction

While thoracoscopic lobectomy is now recommended in early non-small cell lung cancer (NSCLC) (1), the incidence of thoracoscopic sublobar resections (SLRs) is increasing (2), partly explained by several evolutions: (I) surgeons tend preserving pulmonary function and quality of life, which means sparing lung parenchyma whenever possible; (II) the profile of patients is changing: there are more elderly patients with co-morbidities for whom the invasiveness of the surgical procedure must be minimized (3); and (III) in contrast—we have also more younger patients with small tumors for whom parenchymal resection could be discussed in order to spare parenchyma if a second cancer should develop.

Lobectomy remains the gold standard but is responsible for a morbidity of more than 30%, with an average length of stay superior to 7 days (4). In the 119,000-patient series of the National Cancer Database, average mortality ranged from 2–4% depending on whether or not the resection was extended (5). It should also be noticed that we are seeing more and more young patients with multiple ground glass opacities (GGO) and synchronous or metachronous early stage NSCLC. In these patients who undergo surgery for lung cancer, the likelihood of a second operation in their lifetime is very high. Sparing pulmonary function in these patients is important, that means limiting the first resection to a sublobar one (6).

Among the SLRs, we can distinguish between anatomical segmentectomies which will be discussed in this article and wedge resections which will be deliberately excluded. The oncological results of these limited resections are debated. Several Japanese and a few North American authors have reported identical survival after lobectomy and segmentectomy in stage I NSCLC (7-9). But in a large retrospective cohort of 14,473 patients undergoing stage I NSCLC surgery, there was a significant survival gain in the lobectomy group, regardless of tumour size (10). Some authors stress the survival between lobectomy and segmentectomy is the same when a lymph node dissection is performed during segmentectomy (11). While—up to now—these resections have been performed in patients at high risk because of their age, co-morbidities or compromised respiratory function, the most recent studies seem demonstrating these patients have a reduced survival rate, not linked to the type of surgical resection (segment *vs.* lobe) but to a higher overall risk of mortality. In addition, patients intentionally treated with an anatomically segmentectomy combined with lymph node dissection even when they could tolerate a lobectomy would have equivalent survival (12).

Evolutions in the radiological features analysis of the nodule would probably help us determining lesion invasiveness and surgical requires (13,14).

Thus, while SLRs are dramatically increasing, the thoracoscopic approach poses specific problems:

- ❖ Anatomical variations: since most patients may have anatomical variations, surgeons need to be aware of standard anatomy to perform anatomical segmentectomy without compromising the viability of the remaining segments;
- ❖ Absence of manual manipulation of the parenchyma, replaced by instrumental palpation. This leads to difficult—or even impossible—detection of small size tumor, if not immediately subpleural. Similarly, the increasing number of patients undergoing surgery for pure GGO—whose detection is yet difficult when operated by thoracotomy—makes it even more challenging to manage them by thoracoscopy;
- ❖ Altered and or reduced spatial landmarks make some surgical tasks difficult, e.g., delimitation of the intersegmental plane.

It is therefore essential to plan the surgical procedure pre-operatively. By planning is meant: modeling (3D reconstruction, 3D printing, 3D virtual navigation) but also any tracking technique associated with pulmonary resection that will make the procedure more accurate, whatever the purpose, i.e., lesion finding and/or the severing the intersegmental plane [CT scan, ultrasounds, fluorescence, electromagnetic navigation bronchoscopy (ENB)...].

Preoperative modelling is also widely used in other surgical specialties (interventional neuroradiology, ENT surgery, orthopedics, etc.) and has shown being helpful by reducing the operating time, reducing the size of incisions, shortening hospitalization stays, minimizing surgical costs, increasing patient safety and participating in the training of junior surgeons (15,16).

Pre-operative modelling

As recently described by Shimizu in a review on thoracic reconstructions (17), "knowledge of anatomy based on 3D reconstruction is essential for a safe and accurate anatomical segmentectomy". It makes it possible to (I) specify the exact lesion location within a pulmonary segment, (II) define the segmental vascularization and segmental bronchial tree divisions to identify possible anatomical abnormalities that could make the intervention complex or impossible, (III) integrate safety margins to increase the oncological validity of the planned resection, (IV) discuss alternative treatment in compromised patient for whom 3D model predicted a lobectomy for oncological reason.

Pre-operative vascular arterial planning

Already in 2008, some Japanese teams underlined the interest of 3D arterial reconstruction to detect anatomical variations of the pulmonary arteries and try to minimize the risk of bleeding during a thoracoscopic procedure (18). These authors performed 3D reconstructions based on injected CT scan and analyzed the adequacy of their reconstruction by comparing it with the intraoperative findings at surgery. In fact, there are such many pulmonary variations that it is almost impossible to describe a standard anatomy. The development of patient-specific 3D modeling tools therefore plays a key role in this strategy, not only in the preparation of the operation but also as support during the procedure by intraoperatively checking the anatomy on tools like tablets or laptops (19). As early as 2010, the same principles were extended to segmentectomies (20). It should be noted that prior to the introduction of 3D reconstruction, most surgeons limited themselves to simple segmentectomies: lingulectomy (S^{4-5}), superior segment of the lower lobe (S^6) or basilar segmentectomy (S^{7-10}). But the realization of more complex segmentectomies such as one or two basilar segments was only made possible—according to the authors—by the precision of the anatomy helping the surgeon throughout the procedure (19,21-24). These reconstructions also minimize vascular risks during dissection by highlighting unusual and important anatomical variations (25).

Pre-operative venous vascular planning

Anatomical segmentectomy requires a thorough evaluation of the intersegmental veins and venous drainage of the segment to be resected. The numerous anatomical variations may necessitate dissection and division of proximal veins (from the hilum of by the fissure after cutting the arteries) and segmental bronchi. The surgeon can also check on the 3D model there is no venous drainage compromising of the adjacent segment after ligation of the segmental vein (26).

Should 3D reconstruction be done by the surgeon?

Against this option are the important time devoted to image analysis, the insufficient competency in radiology and the need for absolute reliability of the 3D model compared to reality. However, with the progresses of softwares and more and more intuitive tools, these objections will vanish (27). For this option are: the surgeon's independence from an external provider (whether it is a radiologist or an external company) and the possibility of carrying out this type of planning for any thoracic surgery.

Preoperative planning of the resection margin with confirmation of the segment(s) to be resected

Compared to lobectomies, SLRs have an increased risk of local recurrence, as resection margins tend to be closer to the tumor (28). Schuchert *et al.* clearly demonstrated that for patients with a Stage I NSCLC, the results of SLR were comparable to lobectomy, but recurrence was more frequent in patients with a margin/tumor ratio of less than 1 (8).

The distance between the lesion and the staple line of the intersegmental plane is therefore a crucial factor. Some authors have described the use of software to extrapolate a safety margin based on tumor diameter (29,30). On our 3D models, we have developed a virtual safety margin, which sometimes leads to extend the resection to the adjacent segment if the intersegmental parenchymal resection plan seems compromised. This does not preclude the need for an intraoperative frozen section analysis of the staple line in the event of a lesion that appears to be close (31).

Tracking

Preoperative marking of nodules

More and more patients are now being referred to the surgeon with a suspicion of pT1a NSCLC or with GGOs. One of the features of these newly encountered lesions is the difficult detection because of their size and their inconsistency at palpation, particularly for GGO. Different criteria have been established that should lead to use a preoperative localization method, especially lesion size and distance to the pleura (25,32). Several techniques have been described (33) and recently listed again (24,34) to assist in locating peripheral lung lesions: preoperative injection of dyes (methylene blue, lipiodol, colored collagen etc.), metallic markers placement within the lesion (coils, fiduciaries) or hooks, transthoracic or thoracoscopic ultrasound with all their advantages and limitations. Particularly noteworthy are the risks of pneumothorax for CT-guided procedures, the migration of hooks or coils, logistical difficulties related to the transfer of the patient from the radiology room to the operating theatre. These potential complications could be reduced by performing these techniques immediately before surgery in the operating room thanks to hybrid rooms equipped with C-arm CT (35,36) or ENB (37).

Marking of the intersegmental plane

With closed chest surgery, the plane determined by the intersegmental vein—the standard thoracotomy landmark—is much more difficult to identify. The delimitation of the plane according to other techniques is therefore necessary and has been described as follows:

(I) Realization of an inflation-deflation zone once the bronchus has been cut or by direct catheterization of the segmental bronchial stump is the most frequently used method. Tsubota published a slightly different method with inflation of the whole lung, then stapling or ligation of the segmental bronchus, thus trapping air within the segment to be resected (38). Okada *et al.* proposed the use of jet ventilation positioned under elective flexible fibroscopy in the segment to be resected (39), or segmented bronchial ligation with a slip knot method after inflation (40).

(II) Other methods using thermography or a combination of indocyanine green (ICG) and infrared thoracoscopy have been developed (17). After segmental artery ligation, intra-systemic injection of indocyanine creates a fluorescent boundary between viable (fluorescent) and devascularized segments (41,42).

(III) Endobronchial marking by dye injection either under bronchoscopy or assisted by ENB. Conversely, an injection of ICG into the segmental bronchus followed by ligation of the segmental vein creates a demarcation line by maintaining the targeted colored segment. The transbronchial injection of ICG allows the identification of the intersegmental plane not only at the surface but also in the pulmonary parenchyma (43).

(IV) Virtual assisted pulmonary mapping (VAL-MAP), a technique developed by M. Sato et al allows simultaneous marking of the pulmonary lesion to be removed and resection lines on 3D images with an

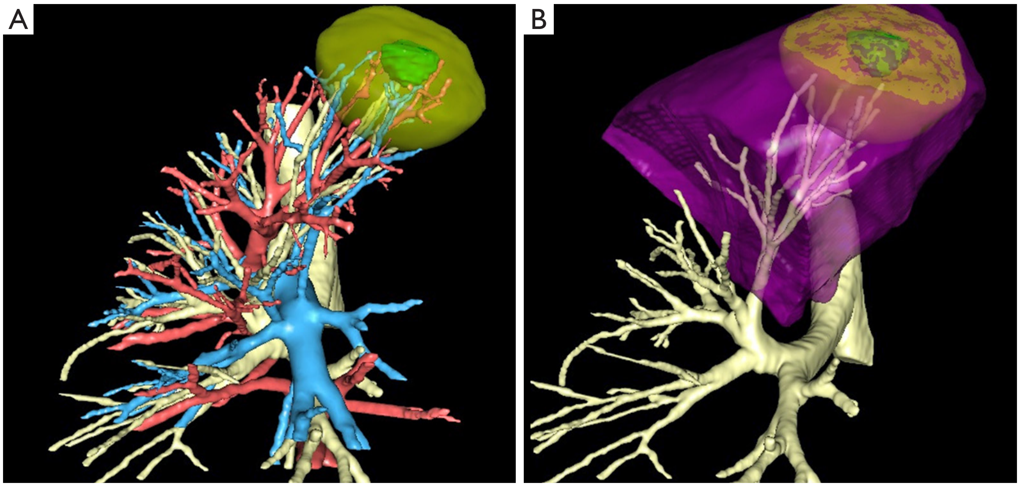

Figure 1 3D reconstructions of the right upper lobe. (A) Vascular analysis; (B) virtual simulation of right S^{1+2} segmentectomy. The safety margin is indicated with a different color than the nodule.

endobronchial dye injected via bronchoscopy (44).

3D printing and augmented reality

3D printing is also experiencing significant interest despite still high costs. In a meta-analysis of more than 600 articles, the benefit of simulation on the theoretical and practical learning of health professionals was clearly demonstrated (45). Three-D printing makes it possible to use a model either for teaching and training in thoracic surgery (46) or for the realization of patient-specific prototypes allowing simulating the intervention beforehand. Its applications in surgery have been highlighted in recent articles (16,27).

Finally, the interactive augmented reality (RAI) initially developed for liver surgery is slowly progressing (34,47). This appealing technique comes up against unresolved technical constraints in thoracic surgery to date, i.e., deflation of the lung. It should make it possible to superimpose the 3D reconstruction on the intraoperative view, which could help the surgeon in the detection of non-palpable nodule or GGO. Unfortunately, the deformities and displacements of the organs make it for the moment inaccurate in thoracic surgery (48).

In practice, what is the planning of an anatomical segmentectomy in our institution?

Our detailed technique was recently published (49).

3D-modelization

Currently, we use an online service that allows 3D modeling of CT-scans from medical DICOM images (Visible Patient™, Strasbourg, France). The images are anonymized and then uploaded by the surgeon to a secure and dedicated web portal. A 3D model based on these images is created according to the surgeon's needs. The 3D model can be used via a dedicated software (Virtual Planning™) and manipulated in any direction whatever the support (laptop, tablet or smartphone). All surgical team members have direct access to the images on their own phone or tablet so that the strategy and technical issues can be discussed together. The software not only allows one studying the main anatomical landmarks in their entirety or separately, but also provides the following useful functions:

- ❖ Evaluating segmental arteries, veins and bronchi preoperatively (*Figure 1A*);
- ❖ Simulating virtual resections by clicking on a selected bronchus (*Figure 1B*);
- ❖ Calculating the volumetry of segments;
- ❖ Calculating and simulating a safety margin, twice as large as the diameter of the tumor, which is represented by a yellow halo around the tumor. This helps visualize whether the planned segmentectomy will match a safety margin, or whether a larger resection should be preferred;
- ❖ Confirming the exact location of the target lesion;
- ❖ Identifying the intersegmental plan.

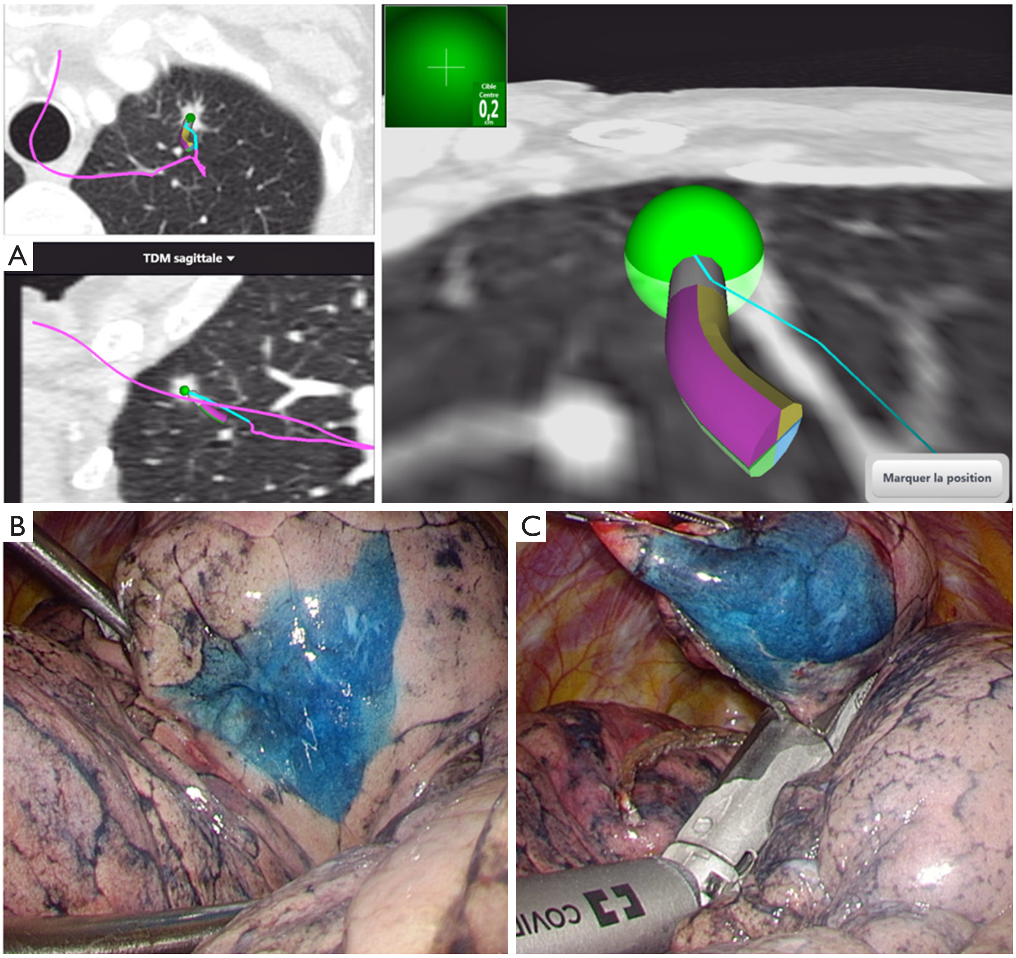

Figure 2 Electromagnetic endobronchial navigation for localization of a subpleural nodule. (A) Planning, navigation and dye marking using methylene blue; (B) thoracoscopic view; (C) wedge resection with intraoperative examination.

Tracking techniques

When dealing with a GGO or a deeply located nodule; we usually track the lesion with blue dye injection under ENB guidance before surgery once anesthesia has been inducted. According to our pre-operative ENB planning, we navigate to the lesion that is overtaken to reach the pleura. One mL of blue dye is injected after purging the navigation catheter. Thoracoscopy is then performed. This colored mark allows us to perform either a needle biopsy or a wedge resection. The specimen is then sent for frozen section examination (*Figure 2*).

Our initial method for demarcation of the intersegmental plan was the use of an inflation/deflation line after reventilation of the whole lung once the segmented bronchus had been severed.

Since then, we added coloration of the entire segment to be resected under simple bronchoscopy or ENB guidance. In practice: all the segmental bronchi of the segment to be resected are catheterized under bronchoscopy and occluded with a balloon to avoid dye backflow. We then inject 1 mL of a blue dye followed by 20 cc of air.

These two endobronchial staining techniques are preferably carried out for "complex" segmentectomies, especially basilar segments and some upper lobes segments (*Figure 3*).

We are currently evaluating ICG systemic injection (at the dose of 0.2 mL/kg, possibly renewed once) after division of segmental bronchovascular elements. Given the ease of use of this method, we feel it could be extended to any segmentectomy including "simple" ones (*Figure 4*).

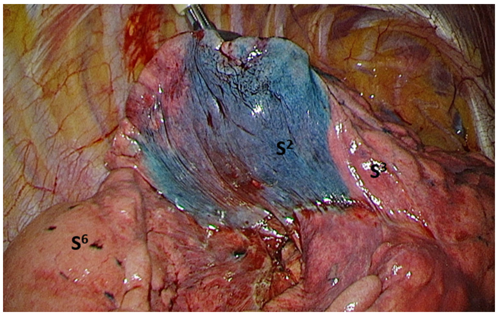

Figure 3 Intersegmental plane delineation of S^2 segment under bronchoscopy using methylene blue endobronchial instillation in the whole segment.

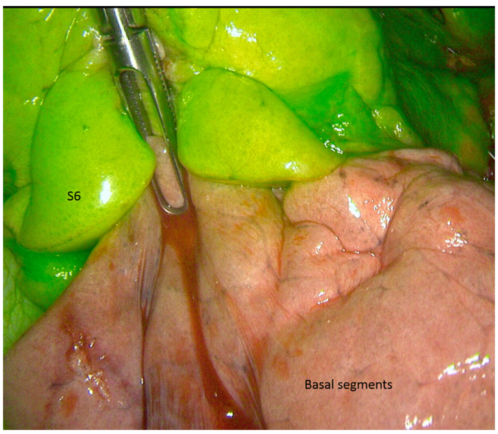

Figure 4 Intersegmental plane delineation between right S^6 and basilar segments using indocyanine green fluorescence.

Conclusions

Performing a SLR by thoracoscopy means confirming the location of the lesion, identifying vascular and bronchial structures, preserving venous drainage of adjacent segments, separating the intersegmental plane and ensuring an oncological safety margin. Preoperative modelling and tracking not only ease these complex procedures but should now be considered as part of the operation. We are most likely only at the onset of these technical developments which, hopefully, will allow us to perform a more and more accurate surgery.

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Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

Informed Consent: The authors confirm that written informed consent was obtained from the patient for publication of this surgical technique and any accompanying images.

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