Chapter

Principles of Pulmonary Lobectomy

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Abstract

Robotic-assisted thoracoscopic surgery (RATS), an evolution of minimally-invasive video-assisted thoracoscopic surgery (VATS), has recently emerged as the standard of care approach for pulmonary lobectomy for lung cancer. Despite increased upfront costs, RATS provides high-resolution, three-dimensional visualization of the operative field and enhanced instrument maneuverability with greater degrees of freedom. Several studies have demonstrated that RATS is non-inferior to VATS and may be associated with more complete mediastinal lymph node dissection and reduced risk of open conversion, length of stay, and intraoperative blood loss. In this chapter, we discuss the fundamental principles of robotic-assisted pulmonary lobectomy, indications and advantages of a robotic approach, and our operative technique.

Keywords: robotic-assisted thoracoscopic surgery, lobectomy, lung cancer

1. Introduction

Advances in *r*obotic-*a*ssisted surgery have revolutionized surgical practice in multiple specialties including *t*horacic *s*urgery (RATS). In the context of resection for lung cancer with curative intent, lobectomy remains the standard of care and most lobectomies worldwide are now performed through a minimally invasive approach, either through *v*ideo-*a*ssisted *t*horacoscopic *s*urgery (VATS) or RATS [1]. *R*obotic-*a*ssisted *l*obectomy (RAL) is an evolution of VATS lobectomy that is becoming increasingly common. Its most remarkable benefits include improved visualization with magnified, high definition, three-dimensional imaging coupled with upgraded instrument maneuverability. RAL has become the standard procedure in many centers and has surpassed VATS as the procedure of choice for lobectomy in the United States [2]. Here, we describe the principles of robotic pulmonary lobectomy for lung cancer.

2. Fundamentals of the da Vinci robotic system

The da Vinci Surgical System is currently the only robotic system approved by the United States Food and Drug Administration (FDA) for lung surgery (Intuitive Inc., Sunnyvale, CA). While originally designed for cardiothoracic surgery and utilized for deep pelvic operations in urology and gynecology, the da Vinci system has become rapidly integrated into multiple disciplines including general abdominal surgery, otorhinolaryngology, colorectal surgery, and cardiothoracic surgery [3]. In 2018, more than 1 million robotic cases using the da Vinci surgical system were performed worldwide [4].

The da Vinci robotic system consists of three primary components. First is a master surgical console controlled by the primary surgeon. This console transmits the surgeon's commands to the robotic instruments through hand controls and foot pedals and offers high-resolution three-dimensional visualization of the patient's anatomy. Second, the patient cart holds the instruments and the camera that are introduced into the patient through ports and are controlled by the surgeon at the master console. Third, the vision cart, is a network system which connects the console to the patient cart and facilitates seamless transmission of inputs from the surgeon at the console to the instruments on the patient, filtering out the natural tremor of the human hand [5]. A second optional console allows tandem surgery and training of residents and surgeons. In thoracic surgical procedures, the two most commonly utilized systems are the SI and the newer XI system. Compared with the older SI version, the XI system is more compact, and has thinner arms, longer instruments, and a swing beam that facilitates a greater range of motion and camera placement in any of the four ports for improved access to all areas of the chest [4].

While the advantages of VATS over traditional thoracotomy for pulmonary resection are well-documented (reduced postoperative pain, faster recovery, reduced risk of postoperative complications such as air leaks, pneumonia, or arrhythmias), comparisons between RATS and VATS are under active investigation [6]. Inherently, RATS allows for high-resolution 3D visualization of the structures in the thoracic cavity and enhanced range of motion and ergonomics compared with traditional straight and rigid thoracoscopic instruments. These advantages in turn allow for easier and complete mediastinal lymphadenectomy and precise vessel dissection [7, 8]. A recent clinical trial of 83 resectable NSCLC cases randomized to RATS vs. VATS demonstrated no difference in the rates of perioperative complications, operative time, or length of stay. However, the median number of sampled lymph node stations, and hilar and mediastinal nodal harvest were significantly greater in the RATS arm [9]. Additionally, a large meta-analysis of 18 studies with more than 11,000 patients demonstrated that RATS was non-inferior to VATS with respect to postoperative mortality, operative time, and overall or disease-free survival [10]. RATS was associated with significantly lower incidence of conversion to open, complication rate, chest tube duration, length of stay, reduced blood loss, and higher nodal harvest [10]. Conversely, RATS is associated with higher upfront investment and overall costs than VATS, which may preclude its widespread use at smaller institutions [10].

3. Indications for robotic pulmonary lobectomy and patient selection

The National Comprehensive Cancer Network (NCCN) and other society guidelines recommend surgical resection for Stage I and II diseases, and select cases of Stage III disease [11]. Lobectomy with hilar and mediastinal nodal sampling or dissection is the standard of care for oncologic resection, either RATS or VATS [12]. Patients should be evaluated preoperatively in standard fashion to define oncologic staging with an intravenous contrast enhanced computerized tomography (CT) scanning of the chest and abdomen, positron emission tomography (PET), and endobronchial ultrasound (EBUS) or mediastinoscopy, reserving brain magnetic resonance (MR) imaging for select cases [12]. Preoperative pulmonary function tests should be performed to ascertain adequate postoperative pulmonary reserve [13]. Indeed, a recent Society of Thoracic Surgeons database study demonstrated that RATS may be associated with decreased postoperative pulmonary complications in high-risk patients with limited pulmonary function, further highlighting the potential value of this approach [14].

3.1 Case selection

Robotic lobectomy is a challenging and high-stakes operation for novice robotic surgeons. It is recommended that surgeons begin their robotic experience with Level I operations (small mediastinal masses, wedge resection, and pleural and lymph node biopsies) before attempting more complex cases. Once some experience has been acquired, the surgeon should perform Level II operations (thymectomy for myasthenia gravis, diaphragm plication, mid-esophageal leiomyoma, chest wall resection) before proceeding to Level III operations (anatomic pulmonary resections, esophagectomy). When beginning to perform robotic assisted pulmonary resections, it is important for the surgeon and the surgical team to carefully select the cases to optimize the learning curve and patient outcomes. Cerfolio et al. suggested the following patient and tumor characteristics that make the initial pulmonary anatomic resections easier and safer [15].

- Tumor <5 cm
- No calcification of lymph nodes
- Peripherally located mass
- Normal bronchoscopy
- No other nodules in lung that need to be identified or resected
- CT scan suggestive of complete fissures
- Located in lower lobes
- No previous radiation
- No previous ipsilateral chest surgery

Once the surgeon and the team have acquired experience with "straightforward" cases, more challenging operations can be introduced, including sleeve lobectomy, segmentectomies, and pneumonectomies. Prior VATS experience with these operations facilitates skill acquisition and confidence, although not absolutely necessary.

4. Relevant anatomy

A deep knowledge of the pulmonary anatomy, and particularly, the spatial relationship between the hilar structures (arteries, veins, airways) and their potential variations, is needed to perform any lobectomy or segmentectomy safely. During a thoracotomy, the surgeon is positioned anteriorly or posteriorly and views the hilum from either the anterior or the posterior direction. In VATS and RAL, the camera approaches the hilum from a caudal direction and the surgeon needs to compensate mentally for this in order to safely conduct the operation. Avoiding misidentification of structures and attention to aberrant or variable anatomy are also of paramount importance to prevent injury that can force conversion to an open operation. In addition, an in-depth knowledge of the vascular anatomy and its variations is extremely helpful when performing technically difficult or challenging cases. Knowing the safe areas for vascular dissection can make a difficult case much simpler and safer.

5. Positioning and anesthesia

Upon arrival to the operating room (OR), patients undergo general endotracheal anesthesia with placement of a double-lumen endotracheal tube. This permits single-lung ventilation during the operation to optimize intraoperative view. The patient is placed in lateral decubitus position and a mild degree of flexion is introduced to the operating table to increase the space available between the ribs and to displace the hip from the chest taking care to maintain the chest in horizontal position. The patient is secured to the table, all pressure points are padded, and the arms are placed in neutral position to prevent stretch injury to the nerve and joints. Arterial line, bean bag, Foley catheter, and axillary rolls are not mandatory, and are used selectively. The patient's chest is prepped with antiseptic solution and sterilely draped. The surgeon's master console is typically near the patient's feet or head, and monitors are positioned in front and behind the patient. An assisting surgeon is positioned on one side of the patient for bedside assistance.

6. Operative technique

6.1 Analgesia and anesthetic technique

Patients scheduled for RAL are typically enrolled in an enhanced recovery pathway protocol. Preoperative analgesia medications include acetaminophen 1000 mg, celecoxib 400 mg, and gabapentin 900 mg or pregabalin 300 mg orally in the preoperative holding area. Patients additionally receive a paraspinal nerve block by the anesthesia service or intercostal nerve block with plain or liposomal bupivacaine intraoperatively. Other adjuncts include dexamethasone 10 mg intravenously, intercostal cryo-nerve analgesia, On-Q pump, and intravenous ketorolac 15–30 mg at the conclusion of the case. Postoperatively patients receive a combination of oral acetaminophen, nonsteroidal anti-inflammatory drugs (NSAIDs), and opioids, reserving intravenous opioids as rescue for severe pain.

6.2 Port placement

In general, five incisions are used for RAL, four robotic and one for the assistant. Non-stapling ports are 8 mm, and stapling and the assistant ports are 12 mm. The following is a description of the port placement for a robotic right upper lobectomy with the da Vinci XI system. All ports are marked with sterile ink before making an incision, although slight changes are often necessary once the intrathoracic anatomy is visualized. Ports are carefully and methodically planned to maximize maneuverability of robotic instruments, optimize access to the critical structures, and avoid internal or external collisions. The tip of the scapula is identified and marked to serve as reference, in case emergent conversion to open thoracotomy is required, avoiding using the ports as part of the incision as they are too low. The carefully planned port incisions are made, and the appropriate trocars are placed (preferably, all robotic ports are placed along the 7th (upper and middle lobe) or 8th intercostal space (lower lobe)). The first port to be inserted is the camera port (Arm 3 for right upper lobectomy). This port is usually placed at the posterior axillary line one or two intercostal spaces inferior and anterior to the tip of the scapula. The thoracic cavity is inspected, and the remaining ports are placed under direct visualization. Arm 1 is placed 3 cm from the spine and one or two intercostal spaces below the tip of the superior segment of the lower lobe to allow unimpeded retraction and manipulation of the lung. This arm, in essence, functions as the exposure or retraction arm. Arm 2 is placed between Arms 1 and 3 or one intercostal space below. Arm 4 is placed as anteriorly as possible and just above the diaphragm. The assistant port is placed between Arms 3 and 4 in an isosceles triangular configuration to allow adequate working space for the bedside assistant. Warmed and humidified carbon dioxide is insufflated to a pressure of 5–8 mmHg through the access port to drive the diaphragm inferiorly and help with lung atelectasis. The robot can approach the operating room table perpendicular to the patient, after which the beam is rotated to the proper position. We utilize a zero-degree camera instead of a 30-degree camera due to its decreased torque, which reduces the chances of intercostal nerve injury [16].

6.3 Instrument selection

Most robotic lobectomies can be completed with three instruments and a stapler (**Figure 1**). For right-sided lobectomies, we utilize a tip-up fenestrated instrument in Arm 1 that serves as the lung retractor. In Arm 2, we utilize Cadiere forceps to manipulate the lung or tissue or a stapler to divide structures. In Arm 3, we place the camera. In Arm 4, we use a Maryland bipolar or curved bipolar dissector. Vascular

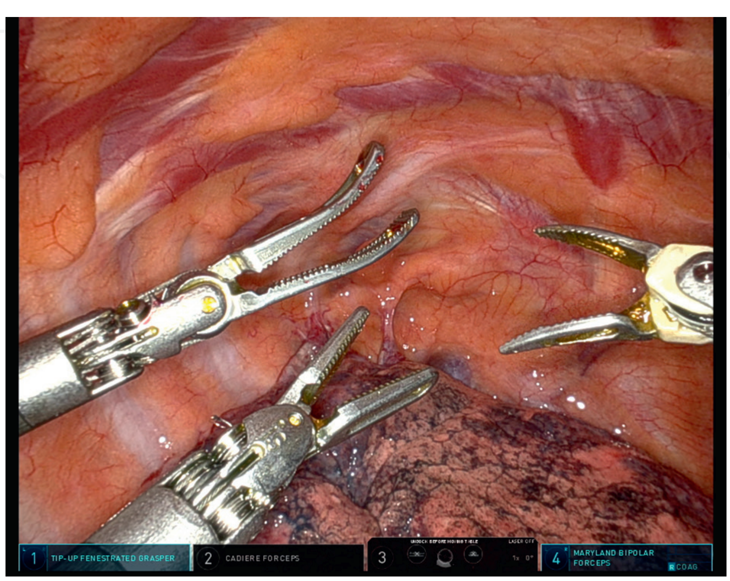

Figure 1.
Robotic lobectomy usually requires only three instruments and a stapler. From left to right the instruments are: Fenestrated tip-up, Cadiere forceps, and Maryland bipolar.

structures are divided with white loads, lung parenchyma with blue or green loads, and the bronchus with green or black loads. Black loads are reserved for thick tissues. Lower profile vascular staplers that are capable to fit through the 8-mm cannulas have received FDA approval and are scheduled to be released in the fall of 2022. All instruments are introduced slowly and under direct vision and positioned toward the apex of the chest to prevent injury to intrathoracic structures. Once in view, the surgeon at the master console can gain control of the instruments and commence the operation.

6.4 Initial assessment

The procedure begins by performing a thorough examination of the thoracic cavity including the chest wall, mediastinum, diaphragm, and the lung to determine if any unexpected abnormalities exist. The target lobe to be removed is visualized and the tumor identified, if possible. If no preoperative diagnosis is available, a wedge resection of the nodule is performed and submitted for frozen section analysis. While waiting for the results of the biopsy (usually 20–30 minutes), the next step of the procedure can be performed.

6.5 Mediastinal and hilar lymphadenectomy

A complete hilar and mediastinal nodal sampling or dissection can be performed in 15 minutes or less. Complete lymphadenectomy is of paramount importance for both adequate pathologic staging and to help expose the vascular structures of the hilum and facilitate their dissection and division. For accurate nodal count and pathologic staging, it is recommended that nodal tissue from one specific lymph node be submitted in one cup, either whole or in fragments as to not count fragments as individual lymph nodes. One cup represents one individual lymph node. Multiple nodes from one station are labeled sequentially (i.e., 7a, 7b).

6.5.1 Right side (9,8,7,10,11,4,2)

The inferior pulmonary ligament is divided from the diaphragm to the inferior pulmonary vein. For this step, robotic Arm 1 (fenestrated tip-up) is used to retract the lower lobe cephalad toward the superior chest and anteriorly. For optimal dissection and less bleeding, it is best to grasp the tissue around the lymph nodes with the Cadiere forceps and use the bipolar energy to cauterize the small feeding vessels around the node. If the node needs to be manipulated, it is best to incorporate the whole node to prevent fracturing and bleeding. Lymph nodes at stations 8 and 9 are removed. Arm 1 is then repositioned and retracts the lung medially and anteriorly to dissect the area of the mediastinum posterior to the pericardium, exposing additional level 8 nodes and the subcarinal space. The nodal tissue in station 7 can be removed incorporating several lymph nodes in the specimen, clearly exposing the left main bronchus and the esophagus. In this area, bronchial artery branches can cause troublesome bleeding and efforts should be placed in identifying and controlling these small vessels with electrocautery. Rolled sponges with a radiopaque marker should be available at all times to help keep the visual field clear of blood. The dissection continues cephalad toward the azygous vein, identifying and removing visible level 10 hilar lymph nodes usually located behind the airway. At this time, it is also recommended to identify the crotch between the right upper lobe (RUL) bronchus and the right lower lobe (RLL) bronchus. At this location, the interlobar node or the sump node or level 11 (superior interlobar node of Rouviere or sump node of Borrie) is dissected and removed, exposing the lower edge of RUL bronchus and the recurrent branch of the pulmonary artery (**Figures 2** and **3**). Arm 1 is then utilized to retract the RUL caudally to expose the superior hilum. This maneuver exposes stations 4 and 2 that lie in the triangle formed by the superior vena cava anteriorly, the trachea posteriorly and the azygos vein caudally (**Figure 4**). Rather than identifying individual nodes in this area, the entire lymph node packet at this location is dissected and removed and nodes can be separated at the back table (**Figure 5**). Care must be taken to identify and protect the vagus nerve at this location running along the trachea toward the tracheoesophageal groove. While looking at the superior hilum, additional level 10 nodes can be identified and removed adjacent to the azygos vein (**Figures 6** and **7**). Areas of dissection are checked for bleeding and gently pack with hemostatic agents.

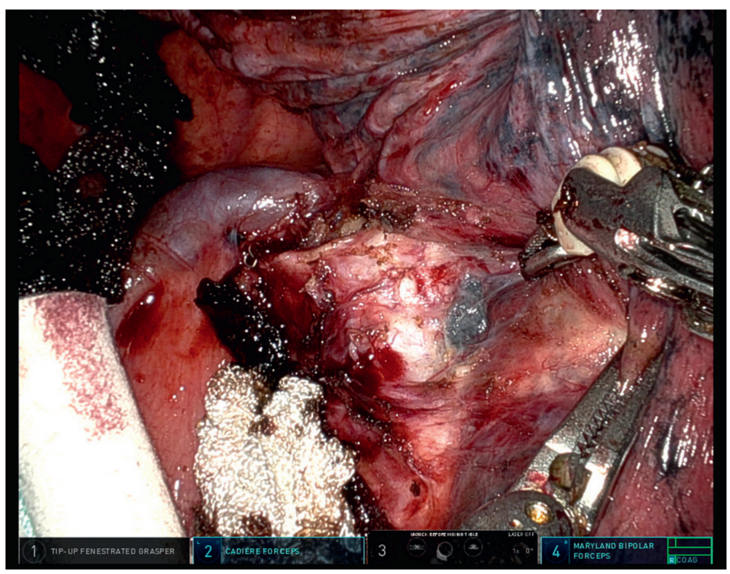

Figure 2.
The right upper lobe and bronchus intermedius are shown with the level 11 interlobar or sump node at the crotch.

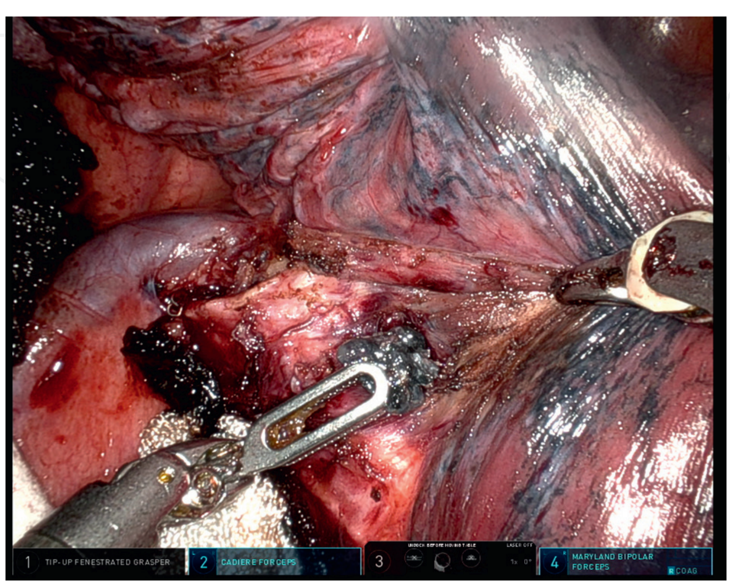

Figure 3.
Dissection of the interlobar or sump node exposes the recurrent branch of the pulmonary artery and is essential to get around the right upper lobe bronchus.

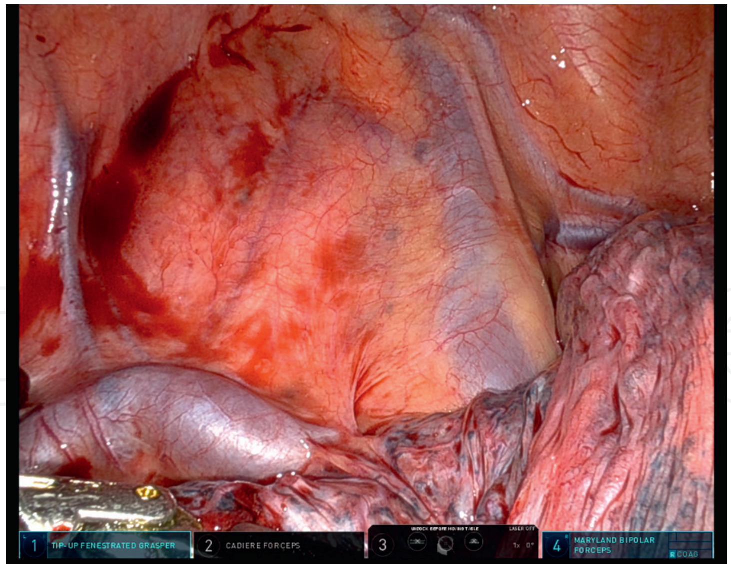

Figure 4.
Caudal retraction of the right upper lobe allows access to level 4 and 2 mediastinal nodes, located in the triangle formed by the superior vena cava (SVC) anteriorly, the trachea posteriorly, and the azygos vein caudally. The phrenic nerve is shown running along the SVC.

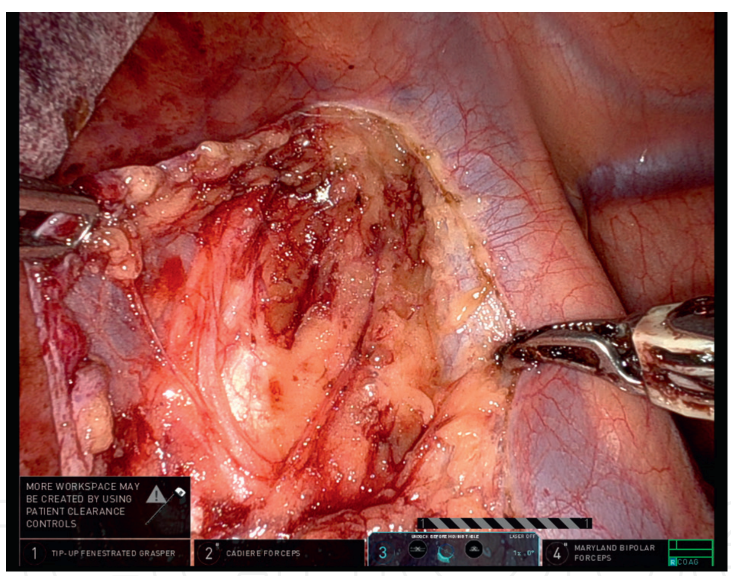

Figure 5.
The entire fat pad in this location is dissected removing several levels 4 and 2 lymph nodes together. These nodes can be separated and placed in individual cups on the back table.

6.5.2 Left side (9,8,7,10,5,6,11)

Similar steps are followed when performing lymphadenectomy for left-sided lung tumors. In this case, Arm 4 will be the lung retractor, while Arms 1 and 3 will be the dissecting instruments. The inferior pulmonary ligament is divided to identify and remove the lymph node on station 9. The node(s) in station 8 are dissected and removed. Subcarinal node dissection on the left side is more challenging than that on the right side and is facilitated, in a lower lobectomy, by division of the bronchus. Lymph nodes at station 7 are accessed in the space between the inferior pulmonary

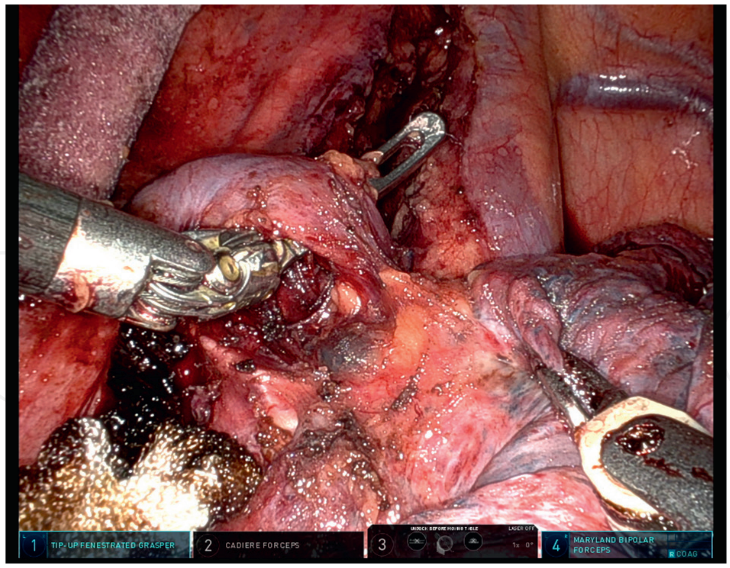

Figure 6.
Additional level 10 or hilar nodes can be dissected between the bronchus and the azygos vein. Elevating the azygos vein ensures all nodes in this area are removed.

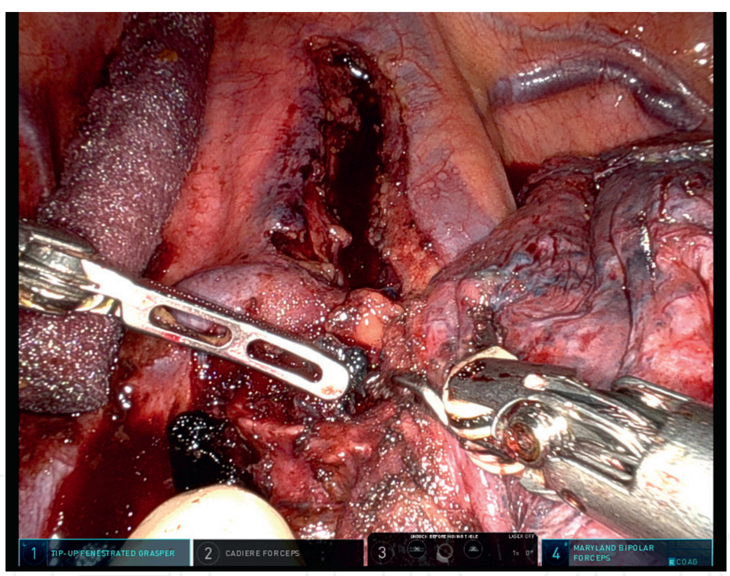

Figure 7.
Additional level 10 or hilar nodes dissected between right main bronchus and azygos vein.

vein and lower lobe bronchus, lateral to the esophagus and in front of the aorta. The lower lobe is retracted medially/anteriorly with Arm 4 during this process. Posterior level 10 and 11 lymph nodes can be dissected and removed at this time and are usually located next to the pulmonary artery at the cephalad end of the interlobar fissure. Finally, robotic Arm 4 is used to wrap around the left upper lobe and pressed it caudally and inferiorly to allow exposure of the superior hilum and dissection of stations 5 and 6. Care should be taken while working in the aortopulmonary window to avoid injury to the left recurrent laryngeal nerve. Station 2 L and 4 L cannot typically be accessed during left-sided lobectomies owing to the presence of the aortic arch, although on occasion 4 L nodes can be identified.

7. Right upper lobectomy

Once the mediastinal and hilar lymphadenectomy is completed, the operation can be performed in one of three ways: 1) traditional VATS approach from anterior to posterior, 2) in reverse order posterior to anterior beginning with the bronchus (bronchus first technique), or 3) superior hilar approach with division of the pulmonary artery (PA) vessels first. A certain degree of adaptability is necessary for performance of RAL as structures may be isolated and divided in a systematic orderly fashion or in the order that the patient's individual anatomy permits. Our preference is to minimize manipulating and flipping the lung as much as possible and therefore, we prefer the latter two options since the dissection started at the back of the lung for the lymphadenectomy.

Retraction of the right upper lobe caudally and inferiorly with Arm 1 helps to expose the superior hilum, which is the last step of the lymphadenectomy on the right side. The mediastinal pleura above the lung at this location is incised to expose the pulmonary vein branches anteriorly and the pulmonary artery branches posteriorly (truncus anterior and posterior branch). The 10R lymph node between the truncus branch and the superior pulmonary vein if visible should be removed or swept up toward the lung, which exposes the truncus branch. The truncus branch is dissected taking care to enter the vascular sheath or plane of Leriche, which makes the vessel dissection simpler and safer (**Figure 8**). At times the entire arterial blood flow to the RUL arises from a single trunk that can be divided with a single vascular load, but more commonly, the truncus anterior is separate from the posterior and the recurrent branch. The truncus is dissected circumferentially with a Cadiere forceps (Arm 4) placing a vessel loop around the artery (**Figure 9**). Temptation must be resisted to use the Maryland or curve bipolar dissector to perform this step as a catastrophic injury to the back wall of the artery may result due to their pointed tip. A tip-up stapler with a vascular load is introduced through arm 2 or 4 and the vessel divided (**Figure 10**). We prefer to avoid placing the stapler from a posterior approach as currently it requires a 12-mm cannula and is more likely to cause persistent pain due to the narrower rib spaces. The posterior

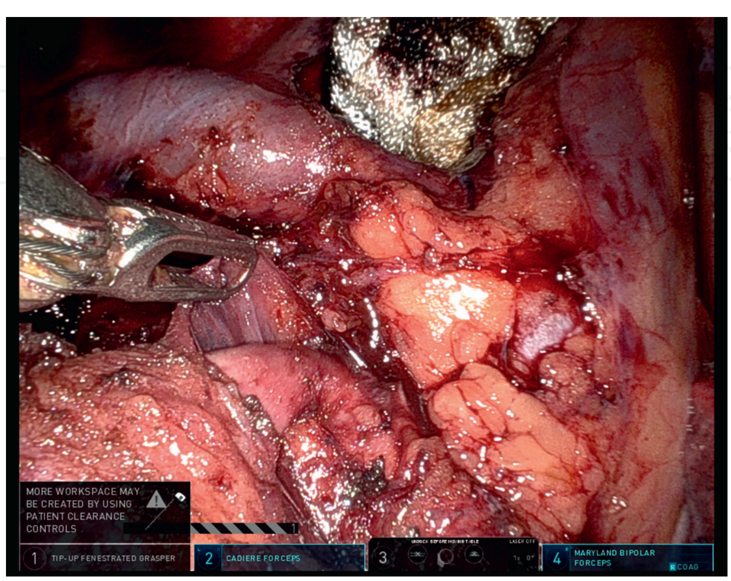

Figure 8.
The arterial truncus to the right upper lobe is shown. The perivascular sheath is incised to enter the plane or space of Leriche. Dissection in this plane makes isolation and division of the vessels easier and safer.

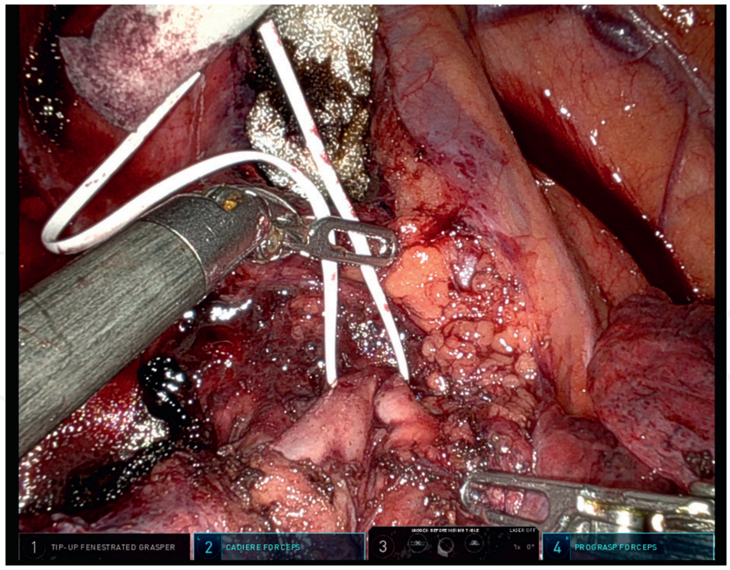

Figure 9.
The arterial truncus has been dissected circumferentially, and the vessel is elevated with a vessel loop at the common origin of the branches.

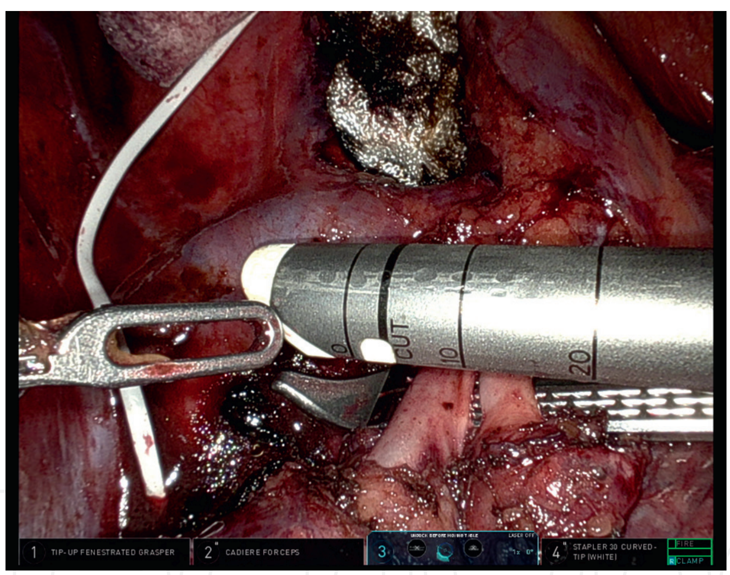

Figure 10.
Stapling of the arterial truncus. The anvil with a ski tip is placed under the artery taking care to avoid lifting or stretching the artery to avoid injury.

branch to the RUL, if present between the RUL bronchus and the truncus anterior, is similarly dissected and divided, further exposing the RUL bronchus. Often there is a level 10 or level 11 lymph node at this location and its removal makes vascular isolation and division simpler and safer. The RUL is returned to its anatomic position and with Arm 1 is displaced superiorly, medially, and anteriorly to expose the RUL bronchus and the bronchus intermedius. Since the sump node at this location has already been removed during the lymphadenectomy, the recurrent branch of the pulmonary artery is easily recognized if present. At times, two recurrent branches are present or origin from a6 must be recognized in order to avoid injury. A branch of the pulmonary vein can also be identified at this location. A complete major fissure or division of the posterior aspect of the fissure can help with the exposure and dissection and division

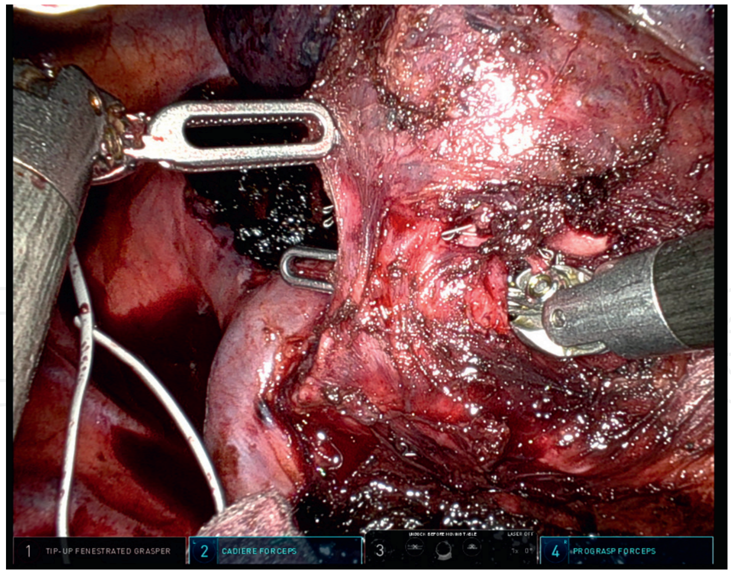

Figure 11.
The right upper lobe bronchus is dissected by placing a Cadiere forceps in front of the bronchus. Since the arterial truncus has already been divided, there is little risk of vascular injury during this maneuver. In the bronchus first technique, this step requires meticulous technique passing the instrument in front of the bronchus to avoid injury to the vessel.

of these vascular structures. Additional level 11 lymph node removal around the origin of the vessels can facilitate vascular dissection and division. Since the pulmonary artery branches in the upper hilum have already been divided, the RUL bronchus can safely be encircled with a vessel loop by passing the Cadiere forceps from the anterior port or Arm 4 (**Figure 11**). A stapler with a green load is exchanged for the Cardiere forceps, and the RUL bronchus is divided (**Figure 12**). At times, the recurrent branch of the pulmonary artery is easier to divide once the bronchus has been transected (13). Division of the RUL bronchus allows to elevate the RUL and expose the posterior aspect of the minor fissure and the pulmonary artery to the right middle lobe (RML) and right lower lobe (RLL) (**Figure 13**). Dissection on the plane of the artery helps

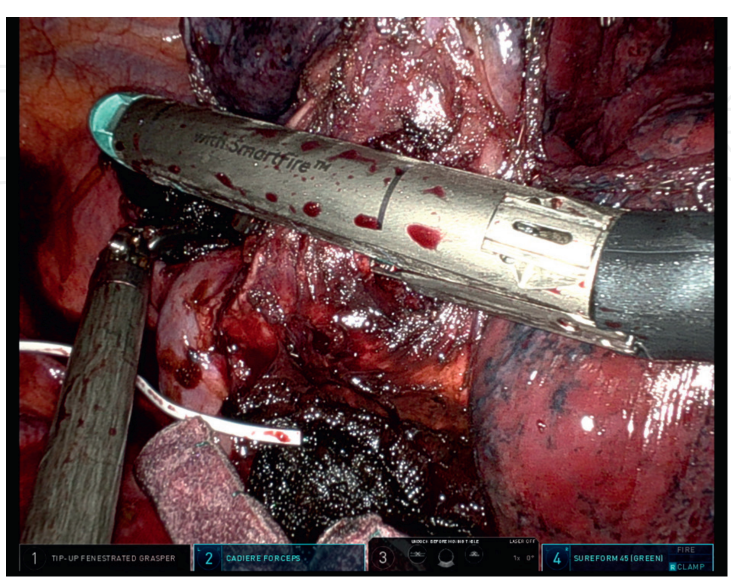

Figure 12.
Bronchi are usually divided with green loads unless they are thick due to prior chemotherapy or radiation. In this situation, a black load may be necessary.

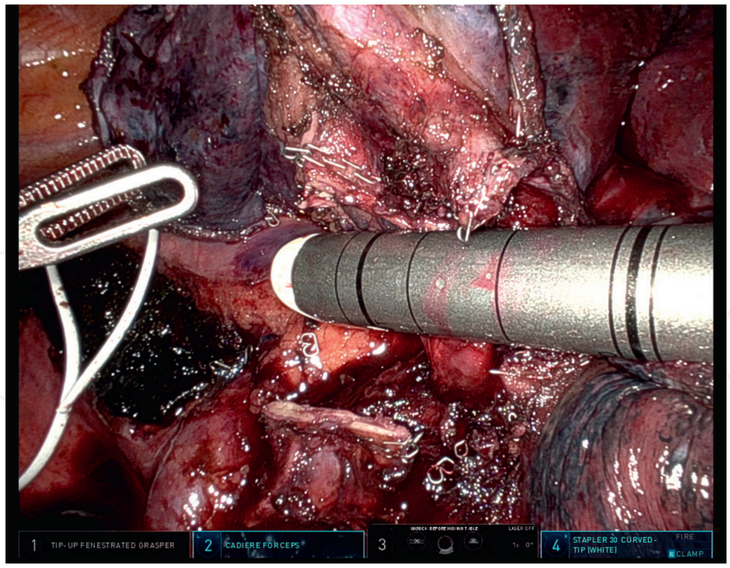

Figure 13.
Division of the right upper lobe bronchus can expose a second recurrent branch of the pulmonary artery to the upper lobe as in this case.

identify the origin of the RML branch of the pulmonary artery and safe division of the posterior aspect of the minor fissure with a stapler introduced through port 2. During completion of the minor fissure, the RUL should be lifted up to ensure that the divided RUL bronchus is included in the specimen (**Figure 14**). Additional blue loads are fired along the minor fissure until the RUL vein is encountered. Once the vein is reached, the branches to the RUL are encircled and divided with a vascular load, leaving the RML in place. Alternatively, if vein visualization is not clear, the lung can be retracted posteriorly with arm 1 and the superior pulmonary vein exposed. The bifurcation between the RUL and RML veins is developed by dissecting it off the underlying pulmonary artery (**Figure 15**). The branches to the RUL are encircled with the vessel loop and divided

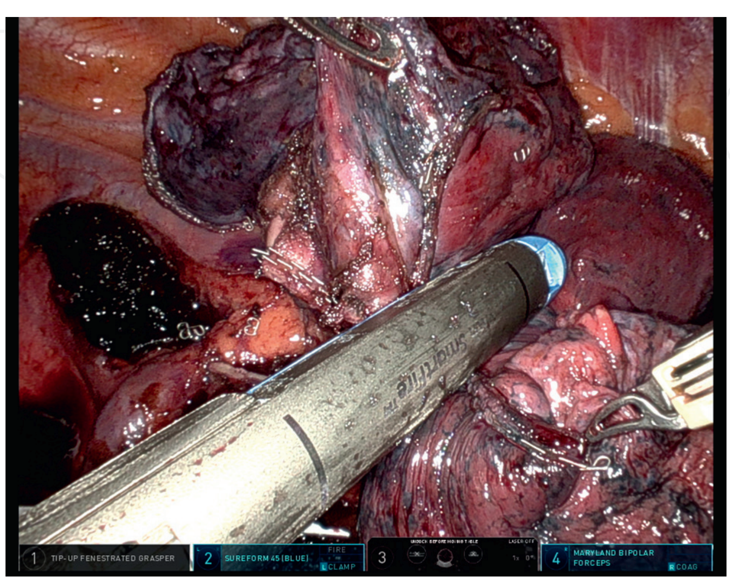

Figure 14.
Stapling of the minor fissure from posterior to anterior placing the stapler above the descending trunk of the pulmonary artery and its middle lobe branch. Care must be taken to avoid injury to the middle lobe vein.

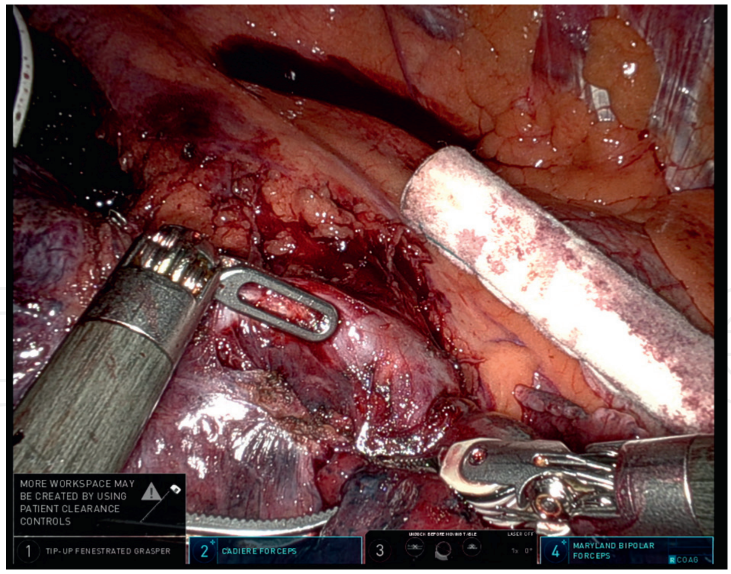

Figure 15.
View of the superior pulmonary vein showing the angle between the upper and middle lobe veins. Dissection posterior to the upper lobe branches is performed taking care to avoid injury to the pulmonary artery located posteriorly.

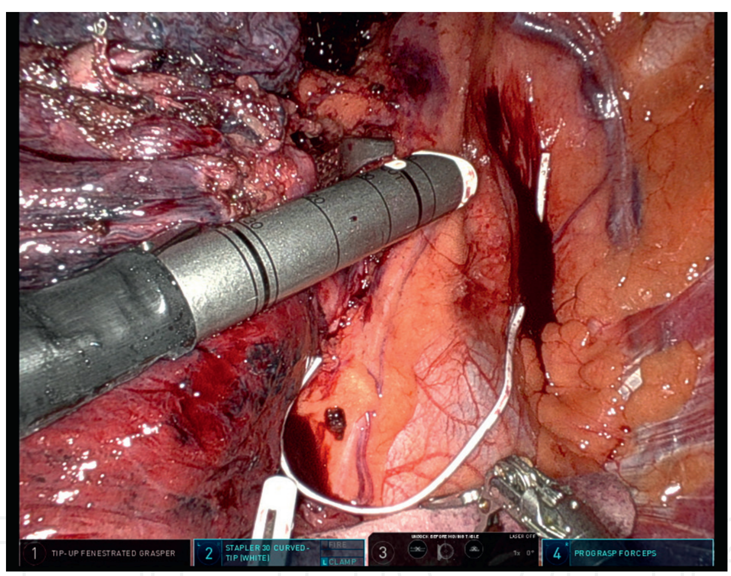

Figure 16.
Stapling of the superior pulmonary vein to the right upper lobe completing the lobectomy.

with a vascular load introduced through Arms 2 or 4 (**Figure 16**). The reminder of the minor fissure is divided completing the lobectomy.

On occasion, particularly after induction therapy or in the presence of adenopathy stuck to the truncus anterior, when arterial dissection is difficult, it is better to divide the upper lobe bronchus with scissors to get to a fresh plane on the artery rather than risk arterial injury. Once the dissection is completed, the bronchus is closed with interrupted sutures. Buttressing of the bronchial closure is encouraged after induction treatment.

The specimen is placed in a bag and extracted from the chest cavity through either the access port or the anterior port (Arm 4). The chest cavity is copiously irrigated with saline, hemostasis is ensured, and a single 24 Fr chest tube advanced into the pleural space. If more than usual oozing or bleeding is anticipated, a larger bore tube or a Blake drain is placed. The fascia and skin over the incision sites is closed in standard fashion.

8. Dealing with an incomplete fissure

In situations where the fissures are incomplete and thick, it is preferable to avoid dissecting it because this will result in bleeding from the lung parenchyma and prolonged air leaks. A better option in these situations is to perform a fissureless or tunnel technique approach to lobectomy [17, 18]. For all three fissures, the tunnel technique starts with dissection between the lobar veins and proceeds cephalad (bottom-to-top technique). This technique can be applied easier to lower and middle lobectomies as the dissection starts caudally by dividing the fissure between the lingula and the lower lobe in the left, or between the lower lobe and middle lobe in the right where there are no vascular structures to divide or at risk, but can also be performed for right upper lobectomy. The division of the caudal and anterior portion of the major fissure is taken to the pericardium between the superior and inferior pulmonary veins. At this point, the lung is retracted cephalad splaying open the divided portion of the fissure to expose the two veins and all the fat and lymph nodes are removed to expose the bronchus and the PA. If a lower lobectomy is being performed, the corresponding vein can be divided at this point, but it is not absolutely necessary. Next, dissection is continued between the bronchi (except for the horizontal fissure) and between the artery and the parenchyma. The lower lobe bronchus usually comes into view first. Dissection continues until a branch of the pulmonary artery to a basilar segment is identified. At this point, the basilar trunk of the pulmonary artery is identified and a plane of dissection or tunnel is established between the artery and the lung parenchyma above. Using Cadiere forceps, the tunnel is created between the anterior surface of the artery and the thick fissure. The ideal dissection plane is close to the artery gently dividing the flimsy connective tissue until the artery is free. Once this tunnel is 3–4 cm in length, the thick fissure is divided with a stapler introducing the anvil in the tunnel. Firing the stapler will open part of the incomplete fissure, and tunneling continues along the artery. The process is repeated until the top of the fissure is reached. Freeing the "exit" of the tunnel first makes the procedure much easier and safer as the anvil can be advanced beyond the exit point without any resistance or obstruction. On the left side the exit point is located at the artery, more specific, between the artery of the posterior segment (a2) of the upper lobe and the apex artery of the lower lobe (a6). The exit point is dissected by first dividing the fused top end of the fissure with a stapler and dissecting the artery at the superior hilum. On the right, the exit can be found at the secondary carina between upper lobe bronchus and bronchus intermedius. We have utilized this approach in a large number of patients without conversion for bleeding (manuscript in preparation). Once the entire fissure has been divided, access to any arterial branches becomes much safer and the operation can continue in seamless fashion.

9. Handling intraoperative bleeding during RAL

One of the most feared events in minimally invasive lobectomy is injury to the pulmonary artery. Cerfolio et al. reported an incidence of major vascular injury of

2.6% during RAL [19]. Novellis et al. reported an overall conversion rate of 6.2% for major robotic lung resections, of which 1.1% (4/338) were due to bleeding [20].

The most common and serious intraoperative bleeding complication during RAL is an injury to the PA. Most commonly these injuries occur during dissection of the artery and are easy to recognize as they occur directly at the point of dissection [21]. Injury can also occur at the time of blind dissection behind the artery or passage of the stapler [22]. In these instances, the pulmonary artery injury (PAI) is usually at the branch point resulting in a more proximal injury, which is more difficult to repair robotically. Most commonly, a central injury to the PA during RAL occurs during left upper lobectomy and is associated with dissection, isolation, and division of the truncus anterior, which is typically large in diameter and short in length.

The risk factors for PAI with robotic lung resection are similar to open or VATS procedures. The risk of PAI is increased in patients who have received induction chemo- and/or radiation therapy, larger tumors, and in the presence of calcified lymph nodes attached to the artery [23, 24]. Pulmonary vein injury is much less common than PAI and is more easily repaired using minimally invasive techniques and will not be discussed further.

The location of the PAI is the key to its management and deciding if it is possible to control the bleeding robotically or conversion to thoracotomy is required. In other words, can the bleeding be controlled and can the proximal PA be clamped safely? In our experience, repairing a PAI robotically is complex and is only feasible for surgeons with extensive experience in RATS and ideally in expert and high-volume centers that also have highly-trained surgical teams. There are essentially two PAI scenarios during RAL: First, the injury is located on the main PA or its proximal branches during upper lobectomy, or second, the injury is located on the lower or middle lobe arteries or on the distal branches of any lobe. The first step in both situations is to immediately control the bleeding with a sponge roll and pressure using the lung itself if possible, and resisting the urge to clamp the vessel with the robotic instruments [25].

Cerfolio et al. described the 4 *"P"'s* as the technique for the control of major vascular injury during RAL: *P*oise, *P*ressure, *P*reparedness, and *P*roximal control [19]. Preparedness can be further expanded to *P*revention of the injury and *P*reparedness of the team to respond to the catastrophic event [26]. A *sixth P* can be added as the vessel is usually repaired with *P*olypropilene suture.

9.1 The 5 "P"'S

Prevention First and foremost is Prevention. Prevention of major vascular injury requires complete and methodical dissection of the perivascular structures, avoiding undue traction of the vessel and being aware of branch points. The strategy of RAL usually starts with a wide mediastinal and hilar nodal dissection with the identification of the proximal or lobar vascular structures. This is followed by dissection of the smaller or segmental vascular branches once the perivascular N1 nodes have been removed and the spaces have been created for the safe passage of the instruments and the stapler. The use of vessel loops for elevation of the vessel and the use of tip-up staplers or guide catheters further decreases the chance of vascular injury. As a general rule, the branch of the pulmonary artery and the proximal portion of the artery giving rise to the branch should be completely dissected before any attempt is made to encircle the branch. This is facilitated by removing all N1 nodes at this location. Decreasing tension on the branch point during dissection and passage of instruments is an excellent technique for avoiding injury to the artery. In general, greater dissection of N1 nodes and perivascular structures leads to safer exposure and control of the pulmonary artery branches and prevention of catastrophic bleeding. The *"P"* for prevention is the most important of the 5 "P"'s.

Preparedness The surgical and the anesthesia teams need to prepare by performing drills such that each team member is assign a role and is ready in the event of vascular injury. It is the responsibility of the primary surgeon to organize and direct these drills for optimal outcomes in case of severe or catastrophic vascular injury. This requires dedicated anesthesia and nursing teams. Thoracotomy trays with several hand-picked vascular clamps must be in the room, and possibly opened and counted depending on the experience of the surgeon. Suture material (Prolene 4-0 and 5-0), pledgets and blood need to be also available.

Poise: Poise is the most critical response to a catastrophic vascular injury. The primary surgeon must remain as relaxed as possible in order to create a calm attitude and transmit confidence to all members of the surgical, nursing, and anesthesia teams. This is only possible when teams have prepared for the emergency ahead of time by running regular disaster readiness drills. In addition, the surgeon can take a few minutes to assign the specific roles and remind the team of the steps to follow in case of bleeding. This can be done right after the instruments have been introduced into the thoracic cavity and before the dissection begins.

Pressure: Pulmonary artery bleeding can be easily controlled by applying gentle pressure as it is a low-pressure system. Attempts at controlling the bleeding by applying the instrument directly to the artery should be discouraged as this tends to enlarge the tear or make the injury worse. The best approach is to have two tightly rolled sponges in the field next to the vessel being dissected. In the event of bleeding, a rolled sponge is placed over the bleeding point with a robotic instrument (usually Cadiere forceps) and pressure is maintained for at least 7 to 10 minutes if necessary. For a minor injury, this maneuver may be all is required. Next, the assistant introduces a tightly rolled sponge with "EVARREST" fibrin sealant patch on one side (Ethicon, Inc. Somerville, NJ, USA). The patch attached to a tightly rolled sponge is grasped by the other robotic instrument [26]. In a swift motion, the sponge in the hand-applying pressure is removed and replaced with the sponge carrying the EVERREST patch. The patch is held over the bleeding point with gentle pressure for 3–5 minutes. Following this, the patch should be left in place and continued pressure applied on the sponge/patch composite by the assistant instrument. The tendency to assess the injury by removing the patch should be avoided until proximal control is obtained.

It is important to emphasize that the experience of the surgeon with robotic procedures should dictate the next steps following control of the bleeding. For the less experienced surgeons, the safest strategy is to maintain pressure control of the bleeding and calmly convert to a thoracotomy.

Safe conversion to thoracotomy: A second trained surgeon is called to the room to help the primary surgeon. Once the bleeding is under control, the camera is disconnected from the robotic arm and moved to the access port for continued visualization of the pleural space and ensure there is no further bleeding. The camera port is usually near the site of the thoracotomy and needs to be removed. While gentle pressure on the roll patch is maintained with the most anterior arm, remove the posterior arms to provide room for the posterolateral thoracotomy, which should be performed calmly and under control. Performing a "crash" thoracotomy while still bleeding profusely is a losing battle that will result in a poor outcome. The chest is entered through the fifth intercostal space directly over the oblique fissure in order to have full access to the hilum and the proximal pulmonary artery. During the time that the thoracotomy is being performed, using the camera port the assistant can introduce a long metal suction to place direct pressure on the rolled sponge and/or sponge/EVERREST patch and to suction excess blood. Once the thoracotomy is performed and the ribs spread apart, a sponge stick can be introduced to apply direct pressure to the artery if necessary. The remaining robotic arms are removed, and the robot is then moved away from the operating table to allow the surgeon and the first assistant gain proximal control of the PA. Surgeons with greater experience can obtain proximal control and repair the vascular injury by robotic or endoscopic techniques. However, it must be emphasized that conversion to a thoracotomy should be seen as the safest technique and conversion should be performed in a timely fashion and not as a last resort.

Proximal control: Two types of PAI dictate the operative approach. Injury to a proximal vessel during a right or left upper lobectomy (injury to the truncus) usually requires temporary control of the bleeding by applying pressure followed by thoracotomy and vessel repair. More distal injuries to smaller branches of the PA during upper lobectomies and those during lower lobectomies can be repaired robotically by following a structured approach or by thoracotomy. For these more distal injuries, once the vessel is hemostatic, the surgeon obtains proximal control by passing a vessel loop around the pulmonary artery, double loop around it, and gently pulling up to completely stop its blood flow. At this point, the patch sponge composite is removed and the injury is repaired using 4-0 or 5-0 polypropylene suture. On occasion, a hem-o-lock can be applied robotically to the proximal site of the injury to obtain proximal control of a smaller branch of the PA. The vessel is transected and the other end is controlled with a clip.

10. Postoperative management

Patients are extubated in the operating room immediately after the operation and are transported to the recovery room. For the first 12 to 24 h, we prefer to keep the chest tube on suction to ensure lung expansion and egress of any blood or fluid. We utilize a multimodal opioid sparing protocol for pain management, which consists of oral acetaminophen, intravenous or oral NSAID's, gabapentin, and as-needed intravenous and oral narcotics medications. Patients are usually able to spend time out of bed in a chair and ambulate on postoperative day one. Standard recommendations also include deep-vein/pulmonary embolism thromboprophylaxis and incentive spirometry. In our practice, chest tubes are removed when output is less than 5 cc/kg of ideal body weight. If air leak is present or output exceeds this parameter, patients are sent home with a smaller collection device such as the Atrium Express Mini 500 dry seal as early as postoperative day 1. In most patients, this can be removed in 2–5 days. Patients are seen in follow-up in our clinic within 2 weeks to review the pathology report, ensure adequate postoperative recovery, and discuss adjuvant therapy or next steps in their treatment plan.

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