Intraoperative Anesthetic and Surgical Concerns for Robotic Thoracic Surgery

Travis C. Geraci, MD[a,*], Prabhu Sasankan, BS[b], Brent Luria, MD[c],
Robert J. Cerfolio, MD, MBA[a]

KEYWORDS

• Robotic surgery • Anesthesia • Complications • Conversion • Technique • Intraoperative

KEY POINTS

- Anesthetic considerations for thoracic surgery are evolving concomitant with the shift from open to minimally invasive surgery, including the use of robotic systems.
- Successful robotic surgery begins with optimal patient positioning and port placement, which are particular to the planned operating and target anatomy.
- Robotic pulmonary resection is aided by new technologies, including the use of contrast agents to localize pulmonary nodules and define the intersegmental planes.
- Catastrophic events during robotic thoracic surgery are uncommon, but surgeons must be prepared to address them effectively, which may include conversion to open thoracotomy.

INTRODUCTION

A robotic approach has been applied to nearly all procedures in the chest, including surgery of the lung, esophagus, and mediastinum, with outstanding short-term outcomes. With this shift in technology, the intraoperative anesthetic and surgical concerns have equally changed. With less surgical stress during minimally invasive surgery, anesthetic monitoring and approaches to pain control have become more conservative. From a surgical perspective, greater visualization of structures on the robotic system has come with the loss of tactile feedback, creating new challenges. In this review, we discuss the intraoperative anesthetic and surgical concerns as they pertain to pulmonary, esophageal, and mediastinal thoracic robotic operations.

ANESTHETIC MANAGEMENT IN ROBOTIC THORACIC SURGERY

The evolving shift away from open thoracotomy to minimally invasive techniques in thoracic surgery has changed the fundamental anesthetic concerns for these operations. Anesthetic management for robotic lung surgery, is similar to the management of patients undergoing video-assisted thoracoscopic surgery (VATS), typically with general anesthetic technique and controlled, one-lung ventilation.

One-Lung Ventilation

During robotic pulmonary resection, selective ventilation of the nonoperative lung with deflation of the operative lung, or one-lung ventilation, provides a surgical space in the closed thoracic

---

Acknowledgments/Funding Statement: Dr T.C. Geraci, Mr P. Sasankan, and Dr B. Luria have no disclosures. Dr R. J. Cerfolio discloses past relationships with AstraZeneca, Bard Davol, Bovie Medical Corporation, C-SATS, ConMed, Covidien/Medtronic, Ethicon, Fruit Street Health, Google/Verb Surgical, Intuitive Surgical, KCI/Acelity, Myriad Genetics, Neomend, Pinnacle Biologics, ROLO-7, Tego, and TransEnterix.

[a] Department of Cardiothoracic Surgery, New York University Langone Health, New York, NY, USA; [b] New York University School of Medicine, NYU Langone Health, 550 1st Avenue, 15th Floor, New York, NY 10016, USA; [c] Department of Anesthesiology, New York University Langone Health, 550 1st Avenue, 15th Floor, New York, NY 10016, USA

[*] Corresponding author. Department of Cardiothoracic Surgery, New York University Langone Health, 550 1st Avenue, 15th Floor, New York, NY 10016.

E-mail address: travis.geraci@nyulangone.org

Thorac Surg Clin 30 (2020) 293–304
https://doi.org/10.1016/j.thorsurg.2020.04.006

thoracic.theclinics.com

cavity. One-lung ventilation can be attained through several different methods, including placement of a bronchial blocker, although use of a double lumen tube is the most effective and efficient and, therefore, most commonly used method.

Ventilation strategies for robotic lung surgery mirror those for any other thoracic surgery in which one-lung ventilation is used. Preoxygenation with 100% inspired oxygen before lung isolation theoretically decreases the nitrogen concentration of the lungs, facilitating rapid lung deflation via expedient absorption of oxygen. Protective single lung ventilation strategies should be used to prevent barotrauma to the ventilated lung and to avoid postoperative pulmonary dysfunction. Different methods exist to determine the optimal tidal volume and positive end-expiratory pressure to be delivered. Titration of the fraction of inspired oxygen and small increments of positive end-expiratory pressure can be applied to prevent and/or treat intraoperative hypoxia.

Operative visualization is improved with the instillation of carbon dioxide into the operative chest. The pressurized pneumothorax achieves a more rapid and permanent deflation of the lungs when compared with passive deflation. Further, a pressured chest deflects the diaphragm into the abdomen created a wider surgical field. Venous return to the heart may be impeded with high intrathoracic pressure, typically occurring only when the pressure exceeds 5 mm Hg. For this reason, a patient's blood pressure should always be check immediately after the initiation of insufflation. When hypotension develops, the operation is held and insufflation pressure is decreased until hemodynamics have normalized. Rare occurrences of carbon dioxide embolism have been reported when the system is erroneously placed in the lung parenchyma.[1] Severe subcutaneous emphysema can result when placed in the extrathoracic tissues.

Monitoring and Access

Patient monitoring for robotic lung surgery incorporates the standard American Society of Anesthesiologists monitors: electrocardiogram, pulse oximetry, capnography, and noninvasive blood pressure cuff.

We do not use arterial lines routinely, but place them selectively in patients with severe cardiac morbidity or for anticipated operative complexity. Traditionally, arterial line monitoring was used in the vast majority of thoracic surgical procedures, both owing to the risk of intraoperative blood loss and to monitor blood gasses during 1 lung ventilation. As anesthesiologists have become more experienced with minimally invasive thoracic surgery, the imperative to reflexively place arterial cannulas for these procedures has largely abated. For more complicated cases, including bilobectomy, esophagectomy, reoperative cases, and more invasive surgical procedures with higher potential for blood loss and hemodynamic compromise, it is prudent to place an arterial cannula for beat-to-beat monitoring of the blood pressure and for the ability to draw arterial blood samples for intraoperative analysis.

A single, medium-sized intravenous line is often sufficient for the majority of cases. Venous access with multiple large-bore intravenous lines, or even a central line, is generally unnecessary, but may be considered for difficult operations, which may complicate intraoperative hemodynamic status, such as patients with sepsis from empyema or esophageal preformation. One caveat to the emphasis on minimizing the placement of lines is the challenge of direct physical access to the patient associated with positioning for robotic surgery. Although the lateral positioning is similar to that of VATS and open thoracotomy, the positioning of the surgical robot often limits access by the anesthesiologist to the patient's arm and face. This can present a challenge if the need for placement of additional venous access or an arterial catheter arises during the course of the surgery. The Xi system is the current edition of the da Vinci robot and provides greater versatility and functionality. The Xi system allows for docking of the robot to the side of the operating table, whereas the Si system requires placement of the robotic cart at the patient's head. With the greater maneuverability of the Xi, patient access for the anesthesiologist is significantly enhanced.

The incidence of postoperative urinary retention in the literature varies from 5% to 70% and is complicated by the lack of consistent definitions, variance in surgical procedures and populations, and differences in the administration of anesthetic agents.[2] Established risk factors include older age, male sex, type of perioperative and intraoperative anesthetics and analgesics administered, and the type and duration of surgery. The placement of a urinary catheter is infrequently required, except in patients at high risk for postoperative urinary retention (patients with benign prostatic hyperplasia) or when the operation is expected to last more than 3 hours.

Pain Management

In the era of enhanced recovery for surgery, the importance of controlling postoperative pain is critical to decreasing postoperative morbidity, decreasing length of hospital stay, and improving patient satisfaction. Enhanced recovery protocols assist the entire perioperative team in planning ahead and minimizing both the magnitude and duration of patients' postoperative pain. Crucial to that goal is a well-designed perioperative analgesic protocol. Our preferred preemptive regimen includes acetaminophen and gabapentin, taken orally before surgery. Multimodal analgesia allows for the synergistic combination of drugs with varying mechanisms of action and helps to minimize side effects by requiring lower doses of the individual analgesic agents. Specifically, the combination of preoperative oral medications and intraoperative nerve blockade allows for the minimization of opioid administration, both in the operating room and in the immediate postoperative period. This strategy minimizes opioid-related side effects and facilitates early ambulation and hospital discharge.

The need for invasive pain management procedures, such as thoracic epidural catheter placement or paravertebral blocks, has decreased with smaller incisions and lower postoperative pain experienced by patients after minimally invasive thoracic surgery. Regional anesthetic techniques help to attenuate endocrine and metabolic responses to the stress of surgery, limiting stress-induced organ dysfunction and pain postoperatively.[3] We routinely perform a subpleural paravertebral intercostal block with bupivacaine hydrochloride (Marcaine). Performance of intercostal nerve blockade is done under direct visualization with the robotic camera. Additionally, we instill local anesthetic at each port site in the subcutaneous tissue as a field block. The optimal admixture of local anesthetic for pleural and subcutaneous blockade is controversial. Presently, we do not feel the need for additives above a long-acting local anesthetic, such as epinephrine, steroids, or liposomal bupivacaine (Exparel). Retrospective studies have shown conflicting data regarding liposomal bupivacaine in patients undergoing thoracotomy or thoracoscopy.[4,5] In a randomized controlled trial, liposomal bupivacaine marginally decreased postoperative pain and failed to provide an opioid-sparing benefit to patients after sternotomy.[6]

Fluid Management

Administration of large volumes of fluid during thoracic surgery is a contributory, if not causative, factor in the development of postoperative complications. A number of studies have shown that fluid administration of more than 2 L is associated with pulmonary edema and acute lung injury.[7] Our goal is to limit fluid volume to less than 1 L for every thoracic surgery case. Fluid requirements or more than 1 L should prompt a discussion between the anesthesiologist and surgeon regarding the operative plan and hemodynamic status.

Intraoperative Communication

Strong communication between members of the operative team is imperative for safe and efficient robotic surgery. During robotic surgery, the surgeon is positioned on the surgeon console, which is typically distant from the patient and anesthesiologist. Despite amplified microphones and operative speakers, communication between members of the team is inherently less intimate and direct than open surgery at the surgical table. Communication must be clear and concise. To help encourage communication, we do not pin up the surgical drapes at the patient's head, but allow the sterile field to fall, permitting a clear line of vision between all members of the team. Talkback techniques to confirm understanding is an effective tool for avoiding errors and miscues. Ambient noise is amplified in the surgeon console and can be distracting. We advise a quiet operating room to maximize team communication, particularly during critical parts of the case. Maintaining a relatively small group of anesthesiologists, physician assistants, circulating nurses, and scrub techs, all of whom are very familiar with the unique elements of robotic thoracic surgery, helps to foster a collaborative atmosphere and to facilitate communication between the members of the team.

PATIENT AND PORT POSITIONING

Safe and efficient patient position is essential for successful robotic thoracic surgery. Despite the operation performed, care is taken to adequately pad the patient's arms and legs, using foam positioners, pillows, and blankets to buffer any zone where the patient's body will be pressed. We attempt to limit the number of support systems used, avoiding the use of beanbags, axillary rolls, or arm boards. The patient is secured to the operating table at the hip, shoulders, upper extremities, and at the legs.

Robotic instruments are inserted via trocars, which are placed between the ribs through intercostal incisions. The arms incorporate remote center technology that anchors the fulcrum of the robotic arms in space, thereby reducing stress to the ribs. Despite the relative stability of the trocars, lateral and pivoting movements of robotic instruments produce pressure on the intercostal nerves, contributing to postoperative pain and dysfunction. To limit nerve trauma, it is important that the robotic trocars are driven straight into the chest, avoiding angulation, thereby limiting pressure on the intercostal nerve. We use a zero-degree camera to continue minimizing the torque placed on the intercostal nerve at the camera port.

Successful robotic surgery also depends on a skilled bedside assistant. Given the coordination required between surgeon, assistant, and the robotic system, a dedicated assistant with familiarity with the conduct of the operation provides continuity and improves efficiency.

The lateral decubitus position is used for robotic pulmonary resection and thoracic mobilization and reconstruction during esophagectomy. A mild degree of flexion is used to increase the space between the intercostal spaces and to displace the hip from the chest, allowing greater range of motion at the assistant port.

Pulmonary Resections

Port sites are initially mapped on the patient to guide placement. The ports are placed in the eighth intercostal space, above the ninth rib: robotic arm 3 (8-mm port) is placed 4 cm from the lateral aspect of the spinous process of the vertebral body, robotic arm 2 (8 mm) is 8 cm medial to robotic arm 3, the camera port is 8 cm medial to robotic arm 2, and robotic arm 1 (12 mm) is placed approximately 8 cm medial to the camera port, avoiding the rectus muscles, just above the diaphragm (**Fig. 1**). The assistant port is triangulated behind the most anterior robotic port and the camera port. Typically, robotic arm 1 is the “right hand,” which controls a bipolar forceps. Robotic arm 2 is the “left hand” and typically controls a grasper, such as a Cadiere forceps. Robotic arm 4 typically controls a tips-up grasper, which is used for retraction and blunt dissection.

Esophagectomy

During the thoracic phase for robotic esophagectomy, the patient is placed in the left lateral decubitus position with the right chest up and tilted forward to allow the lung to fall away from the posterior mediastinum (**Fig. 2**). The port for the right robotic arm is marked at the inferior aspect of the right axilla, just below the hairline, medial to the anterior aspect of the scapula. The arm serves as the surgeon’s right hand, commonly used to control a long bipolar grasper or vessel sealer. The robotic camera port is placed 8 to 10 cm inferiorly to the right robotic arm in the same anatomic plane. The left robotic arm port is placed 8 to 10 cm inferiorly to the camera port, in the same anatomic plane. The left hand typically controls a Cadiere forceps. An additional left-sided instrument port, which is primarily used for retraction, is placed at the posterior axillary line, just above the diaphragm.

Mediastinal Resections

Robotic mediastinal surgery can be approached from the left chest, right chest, or bilaterally. Each access strategy has its own particular advantages and disadvantages. Ultimately, the approach depends on the anatomy of the lesion, most commonly its predominant sidedness, or involvement of critical sided structures such as the phrenic nerve. A supine position, modified with the patient’s ipsilateral side bumped at an approximate 30° angle, is safe and effective for robotic mediastinal surgery (**Fig. 3**). The ipsilateral arm is allowed to lay beneath the operating table on a slim arm board, exposing the operative chest. The contralateral arm is tucked to allow space for the robotic system, which is driven perpendicular to the patient from the opposite side.

Given the limited space in the anterior mediastinum, safe port positioning is necessary to avoid

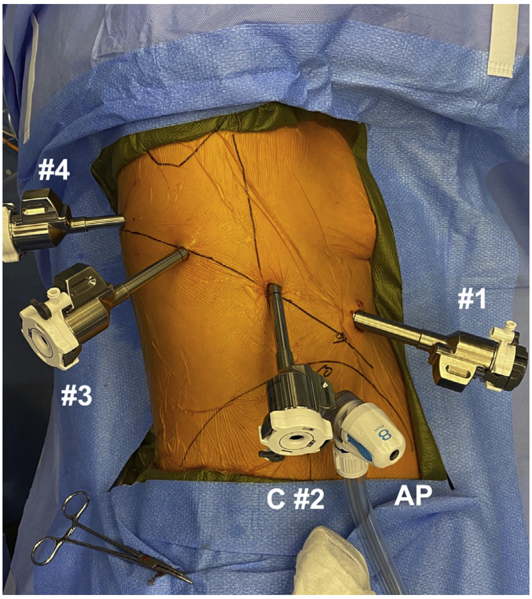

Fig. 1. Port placement for 4-arm robotic right pulmonary resection. The anatomy is mapped out on the patient to guide port placement, including the scapula, posterior axillary line, ribs 8 to 12, demarcation of the ninth rib, and estimated course of the diaphragm cresting to the 10th rib. Robotic ports/arms: anterior port, robotic arm 1, “right hand” (#1), the assistant port (AP), camera port, robotic arm 2 (C #2), posterior port, robotic arm 3, “left hand” (#3), 2nd posterior port, robotic arm 4, “retraction” (#4).

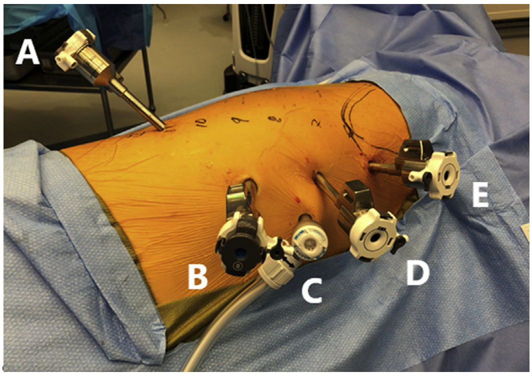

Fig. 2. Port placement for the thoracic phase of a robotic esophagectomy. (A) Additional left robotic arm, (B) left robotic arm, (C) assistant port, (D) camera port, and (E) right robotic arm.

injury, which is particularly critical in the left chest given the proximity of the heart. The camera port is placed first, approximately 1 rib space below the middle of the sternum, lateral to the pectoralis major and breast tissue. The most superior port is placed next, 2 to 3 rib spaces above the camera at the same approximate level. This port must be placed below the innominate vein to have access to the superior anterior mediastinum. The third port is on a more medial plane then the prior ports, approximately 2 to 3 cm below the breast. A 5- or 8-mm access port is triangulated between middle and inferior port. The access port incision can be extended to the inferior port to allow the removal of large specimens.

ROBOTIC PULMONARY RESECTION

The use of robotic surgical systems has accelerated over the last decade as increasing data report excellent short-term outcomes for a number of operations, including pulmonary lobectomy. Robotic pulmonary lobectomy for non-small cell lung cancer has been shown to be safe and effective, with superior short-term postoperative outcomes when compared with lobectomy via open thoracotomy, and relative parity of outcomes when compared with VATS.[8] Long-term outcomes after robotic lobectomy are promising, with a 5-year stage-specific survival of 83% for stage IA non-small cell lung cancer, 77% for stage IB, 68% for stage IIA, 70% for IIB, 62% IIIA, and 31% for IIIB (seventh edition, lung cancer staging) with an incidence of 3% for local recurrence in the ipsilateral operated chest.[9]

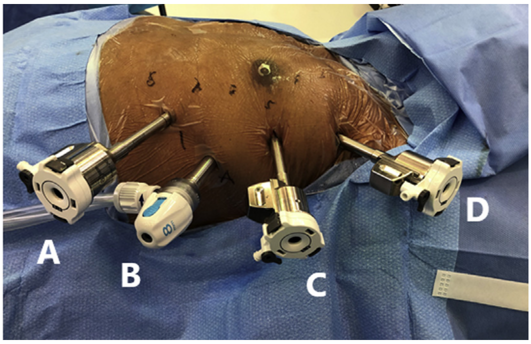

Fig. 3. Port placement for left-sided approach to resection of an anterior mediastinal mass. (A) Inferior port, more medial to the plane of the camera and superior port, (B) 8-mm assistant port, (C) camera port, and (D) superior port.

Localization of Pulmonary Nodules

Small pulmonary nodules (<2 cm), or those with a subsolid or ground glass composition, are often difficult to identify during minimally invasive pulmonary resection. With a lack of haptic feedback and reliance on visual distortion of the parenchyma, intraoperative localization of these nodules is even more difficult on the robotic system. When performing lobectomy, a preoperative computed tomography scan may be enough to determine nodule location; however, during segmentectomy, nodules may be more difficult to locate and may exist between adjacent segments.

There are many methods for intraoperative nodule localization, including radiographically placed wires, coils, or markers, and the use of injected contrast agents. The use of electromagnetic navigational bronchoscopy using near-infrared fluorescence with indocyanine green contrast (ICG) has emerged as an accurate and efficient method for localizing pulmonary nodules (Fig. 4). In a series of patients who underwent planned robotic segmentectomy, we selected 93 for electromagnetic navigational bronchoscopy localization with ICG owing to small nodule size and/or challenging anatomic location (between segments or deep to the visceral pleural surface). Of the 93 patients undergoing electromagnetic navigational bronchoscopy, we successfully identified the pulmonary nodule in 80 patients (86%).[10]

Segmentectomy

Prospective nonrandomized data have shown comparable long-term survival in patients undergoing sublobar resection versus lobectomy with nodules less than 2 cm without nodal metastasis.[11] Two prospective, randomized clinical trials—the Cancer and Leukemia Group B Trial 140503 and the Japan Clinical Oncology Group 0802/WJOG 4607L and JCOG 1211 Trial—are currently being conducted to help address the

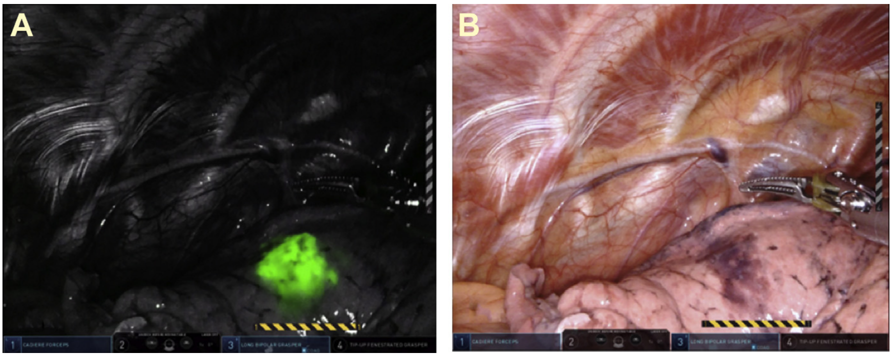

Fig. 4. Localization of a pulmonary nodule in the left upper lobe using infrared imaging and ICG contrast. (*A*) Firefly infrared camera. (*B*) Robotic camera.

oncologic outcomes after sublobar resection versus lobectomy in patients with early stage non-small cell lung cancer.[12]

To help accurately define the intersegmental plane during segmentectomy, thereby assuring the correct division of the anatomic segment and maintaining an appropriate tumor margin, ICG contrast can be administered intravenously after ligation of the corresponding pulmonary artery. A clear delineation of the tissue is illuminated with infrared imaging (**Fig. 5**). Further, this method avoids inflation–deflation of the lung, which obscures the operative view and may be inaccurate given the continuity of the pulmonary parenchyma with pores of Kohn.

Prevention of Air Leak

Most air leaks after pulmonary resection are alveolar–pleural fistulas, a communication between the pulmonary parenchyma distal to a segmental bronchus and the pleural space. Alveolar–pleural fistulas are very common, occurring in about one-third of patients after elective pulmonary resection. Prolonged air leaks increase length of stay and financial costs, and delay chest tube removal increasing postoperative pain and risk of infection. Several risk factors can increase the risk of air leak, including the use of chronic steroids, emphysematous lung disease, and larger resections that leave a pleural space deficit.

During robotic pulmonary resection, it is imperative to avoid puncturing the lung during initial port placement. Despite single lung ventilation, the lung may remain adherent to the chest wall either by normal pleural apposition or from the formation of pleural adhesions secondary to prior surgery, tube thoracostomy, neoadjuvant therapy, or an inflammatory pleural process. If a puncture occurs, these defects should be repaired with an interrupted suture.

Tissue handling to avoid parenchymal tearing decreases the risk of postoperative air leak. Large areas of denuded visceral pleura or lymph node basins with dense adherence to the lung, may benefit from the application of tissue sealants such as Progel (Neomend, Irvine, CA). We use these products selectively, and only in high-risk patients after difficult dissections. A review of randomized trials using intraoperative sealants found

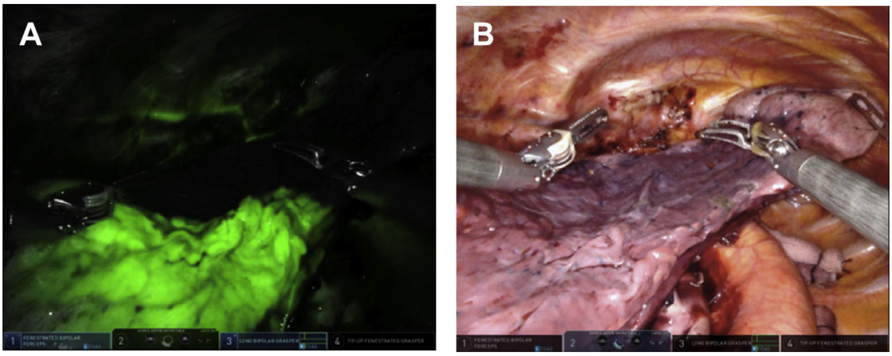

Fig. 5. Delineation of the intersegmental plane between the lingula (illuminated with ICG) and the remaining left upper lobe, during robotic left upper lobe trisegmentectomy. (*A*) Firefly infrared camera. (*B*) Robotic camera.

that these products decreased postoperative air leaks and time to removal of chest drains, however, with equivocal data regarding a decrease in the length of hospital stay.[13]

For the majority of air leaks, water seal is superior to suction and promotes earlier resolution. For large leaks, suction may be required to prevent the development of subcutaneous emphysema or hypoxia.[14] Patients with a large or persistent air leak, which we define as one that delays the patient's discharge, can be sent home with an outpatient drainage device. For these patients, the chest tube can usually be removed in the clinic approximately 1 to 2 weeks postoperatively. It is important to remove the chest tube as soon as possible, to decrease the risk of developing an empyema.[15]

ROBOTIC MEDIASTINAL SURGERY

Robotic mediastinal surgery is typically used for thymectomy in patients with an anterior mediastinal mass, most commonly for thymoma with or without myasthenia gravis. Robotic mediastinal surgery can also be used to resect soft tissue masses such as teratomas, nerve sheath tumors (schwannomas, neurofibromas), lymphomas, thyroid tumors, and parathyroid tumors or cystic structures of the hilum, esophagus or pericardium.

Robotic thymectomy involves resection of the encapsulated thymus and all surrounding perithymic and mediastinal adipose tissue. These tissues are optimally resected en bloc with the bilateral upper horns and lower poles. The borders of resection include the phrenic nerves laterally, diaphragm inferiorly, and superiorly to the cervical border of the anterior mediastinum above the innominate vein.

Anesthetic Considerations

Patients with myasthenia gravis pose unique challenges in the perioperative period. Preoperative titration of anticholinesterase blockade and steroid administration is continued to the lowest levels while maintaining baseline function and symptomatic relief. In the operating room, the neuromuscular relaxation status of patients with myasthenia gravity must be monitored closely. The stress of surgery may exacerbate preoperative muscle fatigue, which can lead to respiratory insufficiency and dependence on mechanical ventilation. At the end of the procedure, the patient is fully reversed of any residual paralysis, to minimize the risk of postoperative respiratory compromise. We typically reverse neuromuscular blockade with sugammadex (Bridion) to ensure complete return of respiratory function.

For patients undergoing resection of large masses of the anterior mediastinum, compression of the airways or heart may lead to complications. A thorough plan for maintaining the airway must be derived before the administration of muscle relaxants, because tracheobronchial obstruction may become apparent only after induction of anesthesia. If airway obstruction develops, several methods may be used to obtain an airway including rigid bronchoscopy, the use of a tracheal tube introducer (bougie), or fiberoptic intubation.

Intraoperative dissection of a large mediastinal mass may cause compression of the heart, leading to significant hypotension. It is critical to maintain communication between the surgeon and the anesthesiologist during manipulation of the mass to anticipate hemodynamic compromise and to relieve any pressure on the heart when hypotension occurs.

Intraoperative Concerns for Robotic Thymectomy

The initial decision during robotic mediastinal resection is whether to approach the dissection from the left chest, right chest, or bilaterally. Often this decision is dictated by the anatomy of the lesion. The right-sided approach offers superior visualization and operative space, owing to the predominance of the heart in the left chest. Further, it offers direct visualization of the superior vena cava, innominate vein, and the origin of the right internal mammary vessels. These structures serve as important landmarks for superior mediastinal dissection during thymectomy.

We have observed, however, that resection of the thymic horns is often easier from the left chest (**Fig. 6**). Additionally, rests of thymic tissue are more commonly found under the left aspect of the innominate vein in the superior mediastinum and in the aortopulmonary window, both of which are often difficult to access from the right chest. From a surgical standpoint, we prefer the left-sided approach to thymectomy in patients with myasthenia gravis or thymoma, given that completeness of resection is the only factor predictive of long-term survival for thymoma and for durable decrease of symptoms in patients with myasthenia gravis.

Preservation of the bilateral phrenic nerves during mediastinal robotic surgery is critical to prevent diaphragmatic dysfunction or paralysis. Observation of the contralateral nerve is facilitated with the use of a 30° camera and decreasing the insufflation of carbon dioxide, which brings the pericardium into the anterior mediastinum. In cases where the phrenic nerves cannot be easily located,

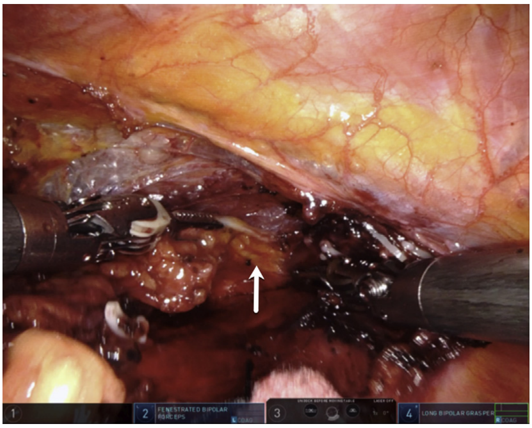

Fig. 6. Dissection of the right superior thymic horn (*arrow*) during left-sided robotic thymectomy.

ICG can be administered intravenously to illuminate the phrenic veins which flank the nerves. Last, an additional trocar can be placed in the contralateral chest to view the nerve via thoracoscopy.

In patients without myasthenia gravis, if the mediastinal lesion involves the phrenic nerve, one of the nerves can be sacrificed to achieve a complete resection, but not both. If a complete resection cannot be achieved, or if both nerves are involved, a reductive surgery is performed. If a phrenic nerve is inadvertently transected, primary suture repair of the nerve can be attempted. In cases of phrenic nerve transection, we do not recommend immediate diaphragmatic plication, because postoperative function remains unknown and the diaphragm lacks redundancy, making plication difficult.

Injury to the innominate vein, which is often obscured by mediastinal fat and the thymus, may occur during dissection into the superior mediastinum. Smaller injuries may be controlled with pressure from a rolled up sponge. Topical hemostatic agents can be used for continued oozing or limited bleeding. More significant injuries may require packing to obtain hemostatic control, allowing time for conversion to an open sternotomy to repair the injury directly.

ROBOTIC ESOPHAGECTOMY

Minimally invasive esophagectomy has demonstrated superior short-term postoperative outcomes versus open esophagectomy. In a prospective randomized comparison of open versus robotic esophagectomy, a robotic approach was associated with lower immediate posterior pain and decreased incidence of pulmonary complications.[16] Long-term oncologic outcomes specific to robotic esophagectomy are not well described and remain a focus on ongoing investigation. Interestingly, lymph node resection has been shown to be greater with a robotic approach, potentially leading to more accurate staging and/or extended survival.

Anesthetic Considerations

For robotic esophagectomy, an arterial line and urinary catheter are placed given the anticipated length of the procedure and possibility of hemodynamic change. A single lumen endotracheal tube is placed initially for the abdominal portion of the procedure and then exchanged for a double lumen tube for the thoracic phase of the operation. Initially using a single-lumen tube decreases the amount of time that the patient has a larger diameter double lumen tube in place.

Management of the Pylorus

During esophagectomy with gastric pull-up, the bilateral vagus nerves are transected, leaving patients susceptible to gastric emptying complications. The addition of a pyloric emptying procedure during esophagectomy aims to limit the sequelae of vagotomy. The optimal management of the pylorus—no intervention, endoscopic dilation, botulinum toxin injection, pyloromotomy, or pyloroplasty—remains controversial. In a retrospective review comparing pyloric interventions during esophagectomy, the omission of an emptying procedure resulted in a greater incidence of aspiration.[17] Further, the functional outcomes and complication profile of botulinum toxin injection were similar to more invasive interventions. Our procedure of choice is injection of botulinum toxin at the pylorus. If postoperative emptying is abnormal, we perform endoscopy with balloon dilation of the pylorus.

Gastroesophageal Anastomosis

The gastroesophageal anastomosis can be completely hand sewn, completely stapled (linear or circular stapler), or a combination of the 2 methods (a linear stapler for the posterior wall and a hand sewn anterior wall). The optimal approach to performing the anastomosis is a matter of debate. We have observed that a completely stapled anastomoses results in a higher rate of stricture. We prefer a linear stapled posterior anastomosis with a hand sewn anterior portion.

The gastric conduit must be aligned appropriately, without twisting or tension. A gastrotomy is made in the posterior wall of the conduit at least 2 cm proximal to the tip of the conduit and distant from the staple line. The remaining anterior wall of the anastomosis is closed using a running barbed locking suture. The anastomosis should be inspected, and any questionable areas should have repair sutures placed. Endoscopy can be performed, and the integrity of the anastomosis checked via air insufflation while submerged in saline. Preserving an omental flap during the abdominal phase allows for wrapping of the anastomosis, which protects the adjacent airway and decreases the risk of anastomotic leak.

Assessment of tissue perfusion can help determine the viability of the gastroesophageal anastomosis. Intravenous injection of ICG contrast illuminates perfused tissue, revealing the optimal area of transection of the conduit for anastomosis (Fig. 7). Investigators have described a 0% leak rate in 39 cases after instituting routine perfusion assessment using ICG to guide creation of the esophagotomy and performance of the gastroesophageal anastomosis.[18] The use of ICG and near-infrared fluorescence imaging can also help with assessment of the vascular arcade during mobilization of the gastric conduit during the abdominal phase of the operation.

CONVERSION TO OPEN THORACOTOMY

A significant intraoperative decision in robotic surgery is deciding when to abandon a minimally invasive approach and convert to an open thoracotomy. Conversion to thoracotomy sacrifices the advantages of minimally invasive surgery and contributes to increased postoperative pain, length of stay, and pulmonary complications. Conversion, however, may become the safest way to proceed after particular intraoperative challenges and complications. The conversion rate for robotic surgery and VATS are similar, ranging from 2% to 10% in institutional series.[19] The decision for conversion to thoracotomy is either the result of an intraoperative complication and/or failure of the minimally invasive approach. The timing of the decision largely depends on a surgeon's experience and the patient's clinical status.

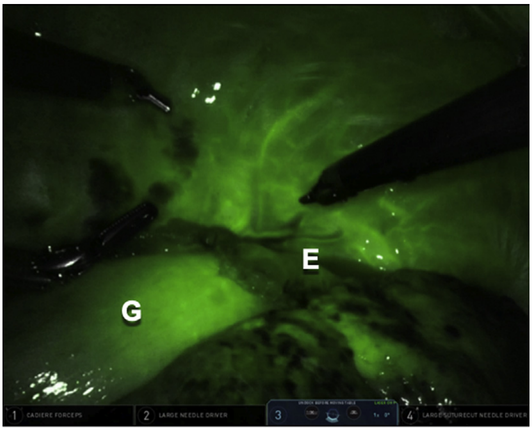

Fig. 7. Visualization of tissue perfusion of the neoesophageal anastomosis using ICG contrast. E, esophagus; G, gastric conduit.

One of the primary reasons for conversion to thoracotomy is when exposure cannot be established safely, most commonly owing to severe pleural adhesions preventing the placement of the robotic ports. Moderate adhesions, such as those encountered in early pleural empyema, can typically be taken down with sweeping of the robotic camera or drainage of pleural fluid with sequential placement of the ports as pleural space is created.

Surgeons may also elect to convert to open thoracotomy to ameliorate frustration during difficult or unusually lengthy cases. Intraoperative challenges such as dissection of dense hilar lymph nodes adherent to pulmonary vessels or a hostile fissure can lead surgeons to convert to an open approach. In a retrospective review of patients undergoing pulmonary resection after neoadjuvant nivolumab, 13 patients underwent minimally invasive resection, of which 7 (54%) required thoracotomy.[20] The authors reported that operative notes in these patients noted dense, vascularized chest all adhesions, and/or dense adhesions in the fissure.

Intraoperative complications, such as hemorrhage, injury to the diaphragm, airway injury, or injury to abdominal organs such as the spleen or liver, may also prompt surgeons to open thoracotomy. Although complications may occur, surgeons must be aware of the potential for problems, anticipate them, and be prepared to address them expeditiously.

Pulmonary Vascular Injury

Given the intimate relationship of the hilar structures in the chest and potential for anatomic variation, thoracic surgeons must be prepared for injury to vascular structures. The pulmonary arteries and pulmonary veins may be injured from a number of mechanisms, including excessive retraction or tearing of a vessel, direct injury during dissection, stapler malfunction, or injury during dissection of an adherent adjacent structure (such as a lymph node or a bronchus). Dark pulsatile bleeding is suggestive of an injury to the pulmonary artery, which occurs in 0.5% to 3.0% of minimally invasive pulmonary lobectomies.[18]

In a multi-institutional series assessing for intraoperative catastrophes during robotic pulmonary resection, 35 events were found among 1810 cases, with conversion to thoracotomy in 31 (89%).[21] An intraoperative catastrophe was defined as any circumstance leading to an emergency thoracotomy after robotic docking and/or requiring an additional major surgical procedure. As expected, risk factors for catastrophic events included higher tumor stage and higher patient comorbidity status. Equally, catastrophic events were associated with increased length of stay, postoperative complications, and mortality. The most common catastrophic event was intraoperative hemorrhage owing to injury of the pulmonary artery or pulmonary vein, with such injuries most commonly occurring in the context of adherent hilar lymphadenopathy. Vascular injury was most common during left upper lobectomy, representing 35% of cases. Importantly, bleeding from the pulmonary artery led to intraoperative death in 2 patients.

Given the gravity of an intraoperative vascular injury during robotic pulmonary resection, it is critical for operating teams to be prepared for major hemorrhage. Our strategy for managing bleeding from a major vessel injury can be summarized as the 4 *P*s: *p*oise, *p*ressure, *p*reparedness, and *p*roximal control. Pressure is applied to the site of vessel injury with a rolled-up sponge (**Fig. 8**). Meanwhile, the anesthesia team and nurses prepare for a possible thoracotomy, and other experienced surgeons are called for assistance as necessary. If possible, proximal control of the bleeding vessel is obtained. The vessel can then be divided with a stapler or the distal injury repaired directly with suture.

Although rare in overall incidence, intraoperative catastrophic events represent critical instances that particularly highlight the value of thorough preparation and robust communication among members of the robotic surgical team.

Airway Injury

Injury to a noninvolved (not divided during the operation) airway, either the proximal trachea, or a distal segmental bronchus, is rare. The most common mechanism of airway injury, however, is a posterior membranous tear from a forceful or oversized double-lumen endotracheal tube. During pulmonary lobectomy, injury to the left or right mainstem airways may occur during dissection of the station 7 lymph nodes or the distal trachea during resection of the station 4 lymph nodes (**Fig. 9**). The use of bipolar cautery decreases the likelihood of thermal injury during dissection of lymph nodes. Airway injury often requires a reconfiguration of airway control, with advancement beyond the defect if possible. Buttressed repair or segmental resection with reconstruction is often required. Mobilization of mediastinal fat, pleural patch, or intercostal muscle are optional adjuncts to place over the site of airway repair.

OPERATIVE EFFICIENCY AND TEACHING

As hospitals and care systems continue to promote value-based care and bundled payments, physicians and surgeons are tasked to optimize value at every stage of patient care. From an operative perspective, we have found that, regardless of the approach (open vs minimally invasive), total operative time is a surrogate for outcomes. We retrospectively reviewed the Premier Healthcare Database for patients undergoing elective pulmonary lobectomy and found that 15-minute incremental increases beyond an operative time of 3 hours were associated with longer lengths of stay (0.12 days) higher costs (total cost $893, operative costs $376, and nonoperative costs $516), more in-hospital complications (odds ratio, 1.05), and increased 30-day readmission rates (odds ratio, 1.02).[22] We believe that the correlation between total operative time and value may be a surrogate marker of surgical competence, teamwork, and efficiency.

Teaching on the Robotic Console

Despite an exacting health care environment focused on perioperative metrics such as patient

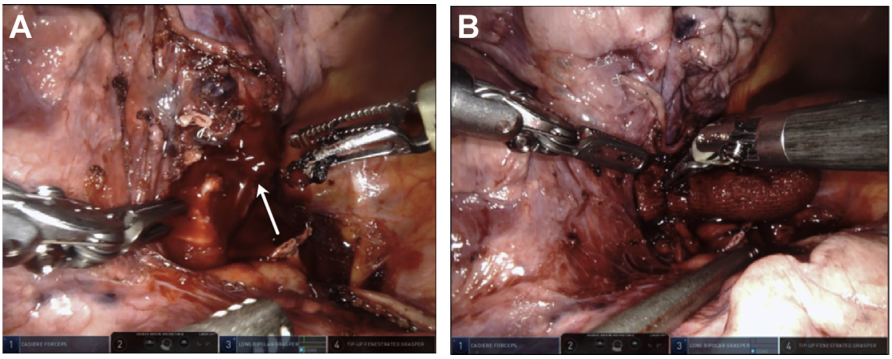

Fig. 8. Intraoperative injury to a pulmonary artery. (*A*) Bleeding from a pulmonary artery branch in the left upper lobe (*arrow*). (*B*) Robotic hemostatic control with application of pressure with a sponge.

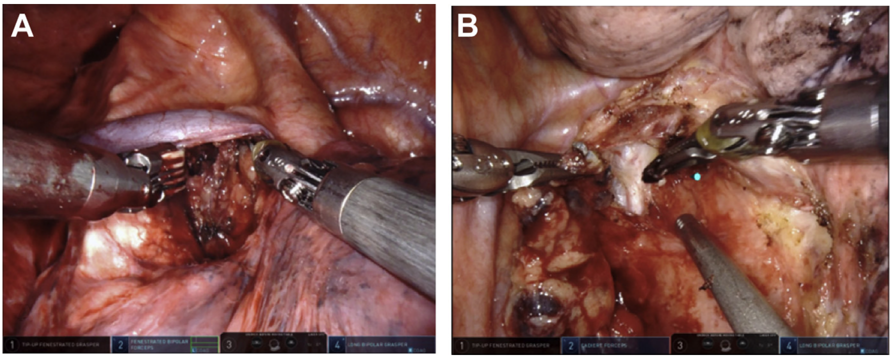

Fig. 9. Robotic lymph node resection. (*A*) Station 4 lymph node resection, with dissection underneath the azygos vein, adjacent the trachea. (*B*) Station 7 lymph node resection with visualization of the left mainstem bronchus.

satisfaction and outcomes, it is incumbent on thoracic surgeons to teach residents how to safely and efficiently perform minimally invasive thoracic surgery. On the robotic system, a second optional console allows for tandem surgery, permitting a clear field of view and fluid instrument exchange for a second surgeon or trainee. Unique to the robotic system, the trainee's operative field and instruments are in the exact orientation and perspective as the primary surgeon. Owing in part to this technology, the operative conduct of robotic surgery can be taught without compromising patient outcomes.[23] For pulmonary lobectomy, we break down the operation into a series of defined steps. Typically, trainees start by mastering dissection of the lymph node stations, then progress to higher risk maneuvers such as robotic stapling and pulmonary artery dissection. Further, video recording of the operation can be easily saved on the robotic system, for later review and analysis of technique.

REFERENCES

1. Hemmerling TM, Schmidt J, Bosert C, et al. Systemic air embolism during wedge resection of the lung. Anesth Analg 2001;93(5):1135.
2. Baldini G, Bagry H, Aprikian A, et al. Postoperative urinary retention: anesthetic and perioperative considerations. Anesthesiology 2009;110(5):1139–57.
3. Kehlet H, Wilmore DW. Multimodal strategies to improve surgical outcome. Am J Surg 2002;183(6):630–41.
4. King NM, Quiko AS, Slotto JG, et al. Retrospective analysis of quality improvement when using liposomal bupivacaine for postoperative pain control. J Pain Res 2016;9:233–40.
5. Khalil KG, Boutrous ML, Irani AD, et al. Operative intercostal nerve blocks with long-acting bupivacaine liposome for pain control after thoracotomy. Ann Thorac Surg 2015;100:2013–8.
6. Lee CY, Robinson DA, Johnson CA, et al. A randomized controlled trial of liposomal bupivacaine parasternal intercostal block for sternotomy. Ann Thorac Surg 2019;107:128–34.
7. Grichnik K, Clark J. Pathophysiology and management of one-lung ventilation. Thorac Surg Clin 2005;15(1):84–103.
8. Kent M, Wang T, Whyte R, et al. Open, video-assisted thoracic surgery, and robotic lobectomy: review of a national database. Ann Thorac Surg 2014;97:236–42.
9. Cerfolio RJ, Ghanim AF, Dylewski M, et al. The long-term survival of robotic lobectomy for non-small cell lung cancer: a multi-institutional study. J Thorac Cardiovasc Surg 2018;155:778–86.
10. Geraci TC, Ferrari-Light D, Kent A, et al. Technique, outcomes with navigational bronchoscopy using indocyanine green for robotic segmentectomy. Ann Thorac Surg 2019;108(2):363–9.
11. Kodama K, Higashiyama M, Okami J, et al. Oncologic outcomes of segmentectomy versus lobectomy for clinical T1aN0M0 non-small cell lung cancer. Ann Thorac Surg 2016;101(2):504–11.
12. Asamura H. Role of limited sublobar resection for early-stage lung cancer: steady progress. J Clin Oncol 2014;32:2403–4.
13. Clark F. Reduction of intraoperative air leaks with Progel in pulmonary resection: a comprehensive review. J Cardiothorac Surg 2013;8:90.
14. Brunelli A, Sabbatini A, Xiume' F, et al. Alternate suction reduces prolonged air leak after pulmonary lobectomy: a randomized comparison versus water seal. Ann Thorac Surg 2005;80(3):1052–5.
15. Cerfolio RJ, Minnich DJ, Bryant AS. The removal of chest tubes despite an air leak or a pneumothorax. Ann Thorac Surg 2009;87(6):1690–6.
16. Sarkaria IS, Rizk NP, Goldman DA, et al. Early quality of life outcomes after robotic-assisted minimally invasive and open esophagectomy. Ann Thorac Surg 2019;108:920–8.

17. Antonoff MB, Puri V, Meyers BF, et al. Comparison of pyloric intervention strategies at the time of esophagectomy: is more better? Ann Thorac Surg 2014; 97(6):1950–8.
18. Hodari A, Park KU, Lace B, et al. Robot-assisted minimally invasive Ivor Lewis esophagectomy with real-time perfusion assessment. Ann Thorac Surg 2015;100:947–52.
19. Brian L. Catastrophes and complicated intraoperative events during robotic lung resection. J Vis Surg 2017;3:52.
20. Bott MJ, Yang SC, Park BJ, et al. Initial results of pulmonary resection after neoadjuvant nivolumab in patients with resectable non-small cell lung cancer. J Thorac Cardiovasc Surg 2019;158(1): 269–76.
21. Cao C, Cerfolio RJ, Louie BE, et al. Incidence, management and outcomes of intraoperative catastrophes during robotic pulmonary resection. Ann Thorac Surg 2019;108(5):1498–504.
22. Ferrari-Light D, Geraci TC, Cerfolio RJ. Prolonged operative time for pulmonary lobectomy predicts worse outcomes and lower value. Abstract presentation #50 at the Southern Thoracic Surgical Association 66th Annual Meeting on November 8, 2019 in Marco Island, FL.
23. Cerfolio RJ, Cichos KH, Wei B, et al. Robotic lobectomy can be taught while maintaining quality patient outcomes. J Thorac Cardiovasc Surg 2016;152(4):991–7.