AME Surgery Series 6A005

Robotic Thoracic Surgery:

A Collection of Clinical Pearls

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James D. Luketich
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Robotic Thoracic Surgery: A Collection of Clinical Pearls (FIRST EDITION)

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The *Annals of Cardiothoracic Surgery*, one of AME's peer-reviewed journals, is lucky to have an author from Rochester, USA. He is left-handed. When he began his training in surgery, he encountered huge obstacles. For example, when using scissors or knotting during a surgery, his actions were the opposite of what was described in textbooks. Therefore, he often "took a beating" from his mentors when performing a surgery.

Later, he summarized his experience and published it in a journal in an attempt to find other surgeons that "suffer from the same fate". Surprisingly, after his article was published, many surgeons e-mailed him, asking him how left-handed doctors should undergo surgical training, and so on. Then he met Professor Tristan D. Yan, the editor-in-chief of *Annals of Cardiothoracic Surgery*, who happens to be a left-handed doctor. Tristan encouraged him to become a heart surgeon because there are steps in cardiac surgery that require the use of the left hand to complete the suture threading technique. Tristan's view was that it was better if surgeons were trained to use both their left and right hands.

A few days ago, on my daughter's first day of kindergarten, I chatted with her teacher for a while; finally, she asked me if there was anything about my daughter that she should take note of . "Please do not correct my daughter's left-handedness," I said, "Just let it be." "Why?" the teacher asked in wonder.

On December 7, 2013, we held the second AME Academic Salon in the Hospital Affiliated to Nantong University. After dinner, Dr. Shen Yaxing from the Department of Thoracic Surgery of Shanghai Zhongshan Hospital invited several attendees to have tea in his room. The elevator was in the middle of the hotel. After we walked out of the elevator, he led us to the left, then to the left, then to the left, then to the left, and finally to the door of his room. Although we were somehow confused and disoriented, some of us did find out that the door was just diagonally across the elevator. We all burst into laughter. Yaxing shared that he took this route the first time he entered his room, and so he decided to bring us on the same route on the second time. Yaxing then said that this was the behavior of a 'typical' surgeon!

During the training to be a surgeon, each step and each action are done under the strict direction and supervision of a senior surgeon. Thus, many surgeons like to affectionately address their mentors as their "masters".

How, then, can you become a master of surgery? In addition to your own intelligence and diligence, the expertise and mentorship offered by a "master" is also very important. Just like in the world of martial arts, there are many different schools that are independent from each other and have their own strength and weakness, and the surgical world is very much the same.

Therefore, it is important for a young surgeon to gain knowledge and skills from different masters by taking in only the essence and discarding the dregs. Therefore, we have planned to publish the AME Surgery series, in an attempt to share with our readers the surgical skills of some prominent surgical teams in China and abroad, as well as their philosophical thinking and some interesting stories. We sincerely hope that our colleagues in the surgical departments find these books insightful and helpful.

Stephen D. Wang
Founder and CEO,
AME Publishing Company

Video assisted thoracic surgery (VATS) has been initially introduced for elementary thoracic surgical procedures. Because of its benefits compared with open surgery in terms of less postoperative pain, decreased postoperative complications, shorter hospital stay, earlier resumption of normal activities, VATS has quickly applied to complex procedures such as major lung resection, thymectomy, esophagectomy, providing same advantages.

However, VATS has some limitations, such as two-dimensional vision and counter intuitive movement using long rigid instruments; these limitations have been in part overcome by the introduction of robotic surgery which with the three-dimensional vision and the endo-wrist technology helped surgeons to perform, with a minimally invasive approach, procedures which require an unnatural angle in hand and wrist with VATS instruments. Though, the use of robots has some pros and cons which are still matter of debate.

The *Robotic Thoracic Surgery: A Collection of Clinical Pearls*, is a collection of papers, recently published by experts in this fields working in renowned Centers all over the world, which provides an exhaustive review of surgical aspects and current debated issues of robotic approach to thoracic surgical disease.

In its three sections, Thymectomy, Esophagectomy and Pulmonary Surgery, the authors discuss different robotic surgical techniques highlighting their positives and negatives, indications to robotic surgery in mediastinal and lung disease, complications related to robotic approach and advantages and disadvantages of using robots over other minimally invasive approach such as uniportal and multiportal VATS.

In this way, the reader has a complete scenario of current robotic thoracic surgery and this textbook may be used by young surgeons as a guide, while they approach this art. Moreover, I guess that also senior surgeons may have a great opportunity to go deep into the topic of robotic surgery, profitably comparing their clinical practice with the reported experiences of the most relevant experts in this field.

Its my honor and pleasure to provide the preface to this textbook, which is the result of the effective cooperation between Colleagues, with a marked interest in this specific subject, and the AME Publishing team, which have taken care of the editing process. Enjoy the interesting reading!

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In the long past, there were only traditional surgery and laparoscopy for patients who suffered from thoracic disease requiring surgery. But with the advent of robotic surgery, surgeons could perform complex procedures with higher precision and better control under the help of highly magnified 3D vision, which consequently allows patients to enjoy a smaller incision and faster recovery. The application of robotic systems in surgery is a significant innovation for minimally invasive techniques and it can overcome the limitations of traditional approaches (1). It is because of all these advantages, robotic technology is more and more widely used in major common thoracic surgery (2).

As the Chief Surgeon and Surgical Director of the Department of Oncology at Shanghai Chest Hospital, I am honored to serve as one of the Editors of this new book *Robotic Thoracic Surgery*: *A Collection of Clinical Pearls*. It is well known that Shanghai Chest Hospital is one of the largest thoracic centers in China with the most complete spectrum of diseases and disorders (3). As a key national clinical discipline in China, it offers a full range of services including traditional open surgery, muscle sparing minimally invasive surgery, video-assisted and robotic-assisted thoracoscopic surgery (VATS and RATS) involving the lungs, esophagus, chest wall and the mediastinum (3). The Co-Editors, Prof. Brian E. Louie and Prof. Giuseppe Marulli, are international leading experts in the field of thoracic surgery. We believe that under the guidance of the editors, this book will be a useful literature to thoracic surgeons and other interested readers.

There are many types of robotic thoracic surgery and we focus on thymectomy, esophagectomy and lobectomy in this book. As robotic thymectomy is considered to be a technically sound approach for thymomas, the book elaborates on robotic thymectomy and shares a multi-institutional European experience in the first chapter. In the next chapter, the current status, the benefits and limitations of robotic esophagectomy are put forward. The longest chapter of the book is devoted to pulmonary surgery. Several articles are devoted to the role of robotic lobectomy in the field of thoracic surgery while the remaining articles focus on robotic lobectomy and segmentectomy for lung cancer.

Though robotic surgery has many outstanding features, it has limited application on extremely huge tumors and tumors close to the heart or great vessels. We sincerely hope that the first edition of *Robotic Thoracic Surgery* will improve the thoracic surgeons' concept and practice of robotic surgery and we do expect that the limitations could be overcome in the near future and their solutions could be collected in the second edition by then.

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The notion of using a robot to conduct surgery conjures up a wide variety of images particularly in the minds of patients and prospective patients who are seeking the best operation. For surgeons, robotics, currently, connotes but a single image but provokes many an opinion about its good, bad and ugly. Regardless of whether you are an adopter or convert to robotics, a newbie just beginning to drive the robotic console or a naysayer dismissing the value of robotics, this new textbook, *Robotic Thoracic Surgery: A Collection of Clinical Pearls*, provides a practical and insightful review of robotic approaches to thoracic surgical diseases.

This collection of articles has been collated from the many publications of the AME Publishing Company including two special issues in the *Journal of Visualized Surgery*. One on robotic surgery with Dr. Robert J. Cerfolio as guest editor and one on robotic surgery for lung resection with Dr. Alper Toker as guest editor. Authors of these chapters come from many countries around the world including Italy, Turkey, United Kingdom, United States, Netherlands, Russia, Hong Kong, Austria, and Japan—a testament to the worldwide interest in robotic surgery.

The hope in combining articles on similar topics from several authors is that this will be an educational platform for young surgeons to learn about different techniques and approaches to robotic thoracic surgery. Additionally, for the expert surgeon the sharing of different approaches and techniques hopefully will inspire further discussion or innovation of the current techniques. For example in the first section on thymectomy, Dr. Marulli and colleagues present a left sided approach to robotic thymectomy while Dr. Suda looks to move from the unilateral approach to a more central viewpoint via the subxyphoid location to approach thymectomy.

This theme of differing robotic approaches is repeated in the section on esophagectomy where Ivor Lewis and transhiatal esophagectomy approaches on the robot are presented. And, repeated again in the section are various approaches to pulmonary resection but it is taken further with discussion and viewpoints from experts on transitioning from VATS lobectomy to acceptance of minimally invasive surgery.

While it is my honor and pleasure to provide the preface (and a chapter) to this textbook, the selection of articles and organization of the chapters has been the hard work of Dr. Qingquan Luo from the Shanghai Chest Hospital. Together with the team from AME Publishing Company, they have assembled an outstanding set of papers from leading surgeons on robotic surgery that represent the current state of the art. I hope that you'll enjoy reading these papers as I did.

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The widespread of robot in thoracic surgery: present and future

Since 2001, when robotic technology was first approved by the US Food and Drug Administration (FDA) (1), the initial targets were considered all the procedures requiring operating in tiny and/or difficult to reach spaces (such as cardiac surgery operations), where an extreme dexterity and precision of instruments are required (2). However, in the last two decades an exponential increase in utilization and acceptance of robotic technology in various surgical fields such as urology, general surgery, gynaecology and thoracic, was observed (3). Now, the majority of thoracic surgical procedures have been successfully performed by general thoracic surgeons using the robotic technology. These procedures include anatomical lung resections (4-6), excision of benign and malignant mediastinal masses (7-8), diaphragmatic plication or resection (9), oesophagectomy for malignant tumours and treatment of benign oesophageal diseases (10).

The success and the growing interest and acceptance of robotic technology stems from several reasons: (I) technical with the highly magnified 3-dimensional visualization, easy manoeuvrability and dexterity of instruments with 7 degrees of freedom, that allow difficult dissections in narrow fields, the physiological tremor filtration (6-Hz motion filter) and the easy standardization and reproducibility; (II) oncological with comparable if not superior results obtained in the field of lung and mediastinal tumours; (III) learning curve and teaching facilities**:** the enhanced technology, with better visualization, the intuitive system and the recently introduced dual consoles make training in robotic surgery an excellent tool with an easier and faster learning curve (11).

The actual major limitation is represented by the high fixed cost of the robotic system and the availability of only one system (da Vinci robotic platform, Intuitive Surgical, Inc., Sunnyvale, CA, USA); however, it is well known that several Companies are working on new and maybe more complex systems that could be introduced in the clinical practice in the very next future.

This collection of clinical pearls in robotic thoracic surgery give us an overview of the state of the art and the most innovative applications of robotic technology in the majority of general thoracic surgery operations. It certainly will stimulate the readers to consider the possibility to increase their skill also in this field.

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The book *Robotic Thoracic Surgery* houses a highly informative collection of articles from the world authorities in robotic surgery of the chest. It encompasses not only the how to perform tips, tricks and techniques, but explore the different robotic approaches to the thoracic cavity. Furthermore, there is plenty of material discussing the reasons, economics and logic for robotic thoracic surgery, allowing a more in-depth understanding of the subject, and policy making when setting up such a program. As the dawn of more sophisticated and refined robotic technology is upon us, involving single port access, soft robots, endoluminal robots, artificial intelligence with big data, nanotechnology and manufacturing, to name just a few; there is increasing acceptance that this will become part of thoracic surgery of the future. As thoracic surgeons, we will need to familiar ourselves with this approach, and embrace it as an important armamentarium for the treatment of thoracic diseases.

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Over the past decade, robotic thoracic surgery has gone from being a sideshow to being commonly used and widely accepted. As the use of robotics for surgery on the lung, esophagus, thymus, and other structures of the chest has proliferated, so has the number of methods for doing so. This collection of articles from leaders in robotic thoracic surgery spans the globe, and portrays the diversity of approaches that have been developed as surgeons have refined the way they perform the operations. As such, a reader of this book can surmise that there is not a single approach that works best–rather, this book's utility is in passing along the accumulated lessons learned over thousands of cases done by dozens of surgeons. Furthermore, this collection summarizes much of the worldwide data on outcomes of robotic thoracic surgery, and the various tables embedded in the chapters can serve a concise and efficient resource for investigators seeking this information. Finally, the reader should take care not to miss the many surgical videos that have been compiled into this volume. If a picture is "worth a thousand words," then a video should count for a million. We hope that this book will be helpful as a technical guide for thoracic surgeons looking to adopt robotics in their practice. For experienced robotic surgeons, even a pearl or two gleaned from this text may prove valuable one day in the heat of the operating room.

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The new era of thoracic surgery

In June this year I had the privilege of meeting Prof Joel Cooper, the greatest living thoracic surgeon. He told me how he finally performed the first successful lung transplant in 1983. It was the 45^{th} attempt in the world! He then told me about the first successful double lung transplant and the first successful transplant in cystic fibrosis and in emphysema. He then told me about all his developments in Emphysema surgery and even how as a resident he created the low pressure endotracheal tube that we all use routinely today. It was so apparent that it must have been a tremendously exciting time to be involved in open thoracic surgery in the 1980's.

I believe that every discipline has its golden era of innovation. For Lung transplantation and in fact also for cardiac surgery this was certainly in the 1980s and 1990s. For interventional cardiology it began in the new millennium and continues with the rapid advancement of TAVI and soon TMVR.

I strongly believe that for minimally invasive thoracic surgery we are at the very midst of our golden era. This golden era really reached a peak with Diego Gonzalez Rivas who shook the specialty. Not with Uniportal surgery but by the speed and enthusiasm with which he managed to change the face of our specialty. Having only invented uniportal surgery in 2011 it is the predominant version of minimally invasive thoracic surgery across Asia and in many parts of the world. He showed us that change does not have to be slow and does not have to wait for 3-year multicentre trials. Combined with passion and YouTube, he showed that we can share ideas and develop new concepts very rapidly with the new era of multimedia sharing of cases, videos and sparks of genius!

Minimally invasive thoracic surgery was created in 1992 but throughout the 1990s and the early millennium adoption was slow, and hampered by inadequate stapling, vision and the lack of any specialised instruments. But in the UK utilisation of VATS lobectomy has gone from 9% to 50% in only the last 5 years, as our instrumentation, mentoring, and specialisation has taken off. Over the next 5 years I believe that this figure for VATS will actually become static and then reverse as the robotic figures increase exponentially from less than 5% now to around 50% by 2023. But even what we call 'robotics' today will not be the robotics of 5 year's time, as at least 8 new robotic systems come onto the market over the next 3 years. They will miniaturise, they will crash in price, they will bring us back to the patient's bedside, or they will overlay imaging, or they will provide safety warnings or enhanced pre-operative planning or the ability to rehearse the operation in advance. They will certainly transform training and bring us into line with the flight simulator model of the airline industry and remove the need for us to train on patients, and instead train on simulators.

But don't think that the patient profiles will stay the same while we develop our instrumentation and techniques, as they will not. Lung cancer screening will transform the type of patients that we see to predominantly very early lung cancers. Navigational Bronchoscopy will mean that someone (hopefully a surgeon) will go in bronchoscopically, take a biopsy and then ablate or freeze that nodule, and then sample all their N1 and N2 nodes at the same sitting. Then we will just follow the patient up, armed with their full list of available targeted therapies should they relapse. Advanced Surgery will be reserved only for patients with areas of resistant mutations after multiple rounds of targeted therapy. (These operations will be highly complex as they will have dense adhesions as immunotherapy causes an intense inflammatory reaction around tumours!).

So over the next 15 years we must all be very much ready for constant seismic change in our specialty and be prepared to move with the times, adopt new technology fast, learn navigational bronchoscopy, and understand the multiple targeted therapies, and learn new ways to operate on advanced cases. We will not be able to stay complacent or happy with our current 3 port VATS technique with open instruments, therefore every surgeon needs to be watching for each latest development as it happens.

Thus I hope this has set the scene for you to understand why it is so important to know what is on the horizon at the moment. Thus I will share some of the latest developments that I have seen and encourage you to get on YouTube or start to ask about them and plan to evaluate some of the new technologies as they come out.

Firstly I will address the new robotic systems. There are 8 new platforms to look out for. The big companies are investing very heavily in high quality robotic systems to rival Intuitive in the future.

The Medtronic Robotic System is currently called 'Hugo' and is a neat plug and play design with independent arms on modules that can be wheeled to the patient and a surgeon console that can also be moved fairly freely. The major advantage that the Medtronic system will have over the competition is outstanding compatibility with its range of Covidien staplers and their energy devices and the excellent network of support already available provided by Medtronic. Look out for working versions of this platform in 2019.

The second giant is the Ethicon-Google pair up in the form of a company called VERB surgical (www.verbsurgical.com). This is I think the most ambitious project of all of the start-up companies. With the energy of Google, and actually being developed in Google's original office buildings, there are visionary features being developed like intelligent machine learning, google hangouts, multiplatform sharing of videos in active development. The system itself is rumoured to have the arms coming out from under table and the company itself is describing it as being 'always there are always on' and being a whole new way of performing integrated surgery, bringing in scan data and perioperative data into one unified system. Sounds impossible? Well, Google have done it with Google everything from Google Earth, to Google Hangouts, to Google Translate, Google Classroom etc so I am sure they can do it with everything in a hospital! Together with total compatibility with everything that Ethicon have to offer, this will be an incredible platform of the future. Genius like this takes time, so 2020 or later may be the first time that you will be able to see it working on patients, but you should probably start saving now as this will be a Ferrari not a Ford Focus!

Transenterics have a currently working robotic platform that is in clinical use called the Senhance surgical system. www.transenterix.com. They feature 5 mm instruments, each arm on a separate moveable gantry, haptic feedback and a camera controlled by your own head movement. However, they promote themselves as a cost sensitive solution and therefore have made some compromises in the system including many of the instruments not being wristed. In addition, the controllers look like laparoscopic instrument handles and thus many describe the system as a remote laparoscopic instrument holder, but with quite a large price. As a result, they are still loss making and their website reports the sale of only 4 systems in the 2nd quarter of 2018 at $1 million each and they are losing an adjusted net loss of $11 million per quarter as a company at the moment.

AvateraMedical (www.avatera.eu) are a German company who are developing a 4 arm robot from a single cart in a similar fashion to Intuitive with a closed surgeon console again similar to Intuitive. Not much is known about this system, other than it is very similar to the intuitive system! And not to be outdone, there is another system called REVO-1 manufactured in Republic of Korea that was launched for clinical use in march 2018. www.revosurgical.com. This takes the similarity of its system to the Inituitive system to a new dimension! It is a 4 arm, single cart system, with a very similar closed surgeon console and the main differentiation is just price. It couldn't look more like an Intuitive Xi if it tried!

Medicaroid are a Japanese company (www.medicaroid.com/) whose main interesting factor is that they have paired up with Kawasaki, the giant robotic manufacturer of car assembly plants. There are rumours online that it may have the arms in the table but I don't know much about this system and currently there is little known about developments of this system or release timings do I don't think we will see anything till after 2021.

But I have left the most exciting systems to the end of this list.

Cambridge Medical Robotics have a working system called Versius and are ready to install this into 6 UK hospitals in the next 6-12 months. www.cmrsurgical.com. My own hospital hopes to be one of these 6. This was designed in reverse to usual systems as they asked the question as to what they thought the UK system could sustain financially for a robotic system and they came up with the answer that it could not sustain any upfront cost and the per case costs had to be the same as current reuseable laparoscopic instruments. Thus they embarked on designing a system that did this. 200 Cambridge Graduate Engineers have now designed an immaculate system with 5 mm robotic arms, each standing on their own small portable modules to be wheeled up to the patient. It uses any standard endoscopic ports and has a surgeon's console with hand controls far more like an Xbox than a cardiac surgeons Castro needle holders. It is very small and portable to any operating room, But the price structure is the real game changer with no up-front costs and instruments that time in hours of use, not number of cases.

But the final king of the future in thoracic surgery will surely be the Intuitive Da Vinci SP surgical System. This finally has FDA approval for urology and is the holy grail for thoracic surgery. With 3 robotic arms and an amazing snake camera all through a single 2.5 cm port that spread apart on entering the chest, finally uniportal robotics is here, which will not only make uniportal robotics far more simple for all users but will open up the reality of subxiphoid-only uniportal robotic surgery, which must surely be the least invasive approach in Thoracics possible. Currently subxiphoid uniportal is performed in a very tiny minority of cases due to its extreme technical difficulty, it will now be possible to do this for virtually every thoracic case… as long as you have around $3-4 million to spare!

But finally I would like to caution you against assuming that pure robotics is the only future. We will see a melding of VATS and Robotics with the advent of wristed VATS instruments. I have had the pleasure of using the flexdex surgical instrument (www.flexdex.com) for lobectomy, thymectomy and diaphragm plication. Currently version 1 is only a needle holder, but version 2 will have Maryland graspers with bipolar energy, Cadiere style graspers, hooks, scissors and maybe even suture-cut needle holders. And at only a few hundred dollars each, this brings wristed instrumentation to all VATS Surgeons. They are FDA approved and CE marked.

And this is not the only company working on Wristed Instrumentation. A company called livsmed (www.livsmed.com) from Republic of Korea have been demonstrating a suite of fully wristed instruments that can be used in both hands that seem to be very similar to robotic marylands, graspers and needle holders. They tell me that they already have a full suite of instruments and have performed cases clinically in Republic of Korea although they are not FDA approved or CE marked.

Thus one alternative glimpse of the future is to be having two wristed instruments in your hands and a robotic camera holder such as autolap or freehandsurgical (www.mst-sys.com or www.freehandsurgeon.com) with a 3D Camera. With this set up you have every element of a robotic system (Wristed instrumentation, control of the camera, 3D vision) and none of the disadvantages (assistant required to perform the stapling, surgeon away from the patient's bedside) and because you do not need an assistant, this set up will actually cheaper than the VATS surgery offered today, and safer than current robotics!

So the future of minimally invasive surgery is exciting and very fast moving. The future of thoracic surgery will certainly change quickly so we must move with it. I have mentioned some of the novel robotic and wristed VATS instruments that will be available very soon but if I had one piece of advice for all surgeons, it would be to be looking at navigational bronchoscopic systems. The current available system is called Superdimension www.superdimension.com from Medtronic, but new entrants to the market are already coming including the $700 million company called Auris (www.aurishealth.com) who have developed a 'robotic' bronchoscope purely because they see the future of biopsy and ablate. I have also seen a 3 mm filament for a bronchoscope with 100× magnification allowing on-table real-time microscopy in the lungs to identify tumour tissue as opposed to inflammation or normal alveoli. These developments are just around the corner. All these systems require general anaesthesia and we must learn the lessons of the cardiac surgeons who were slow to enter the catheter labs and who lost the leadership in TAVI and revascularisation. We must enter the world of bronchoscopy and embrace this more minor procedure with as much enthusiasm as subxiphoid uniportal robotic surgery!

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Abstract: Thymectomy is the most frequent surgical operation involving the mediastinum, both for the treatment of thymic tumors and for the multidisciplinary management of myasthenia gravis (MG). Different surgical approaches have been described, either traditional open approaches or minimally invasive ones. Robotic thymectomy represents a further step in the evolution of minimally invasive surgery. Available data show that robotic thymectomy may be considered a safe and feasible operation, with encouraging long-term results in myasthenic patients and promising results in patients with early stage thymoma, both in terms of surgical and oncological outcomes. We present the surgical technique of robotic thymectomy that we apply for patients affected by myasthenia gravis and early stage thymoma.

Keywords: Thymectomy; thymoma; robot; myasthenia gravis (MG)

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Introduction

Thymectomy is the main operation in the treatment of thymomas. In addition, since in the first decades of the twentieth century was observed an improvement of myasthenia gravis (MG) after thymectomy, this procedure has gained importance in the multidisciplinary treatment of MG, becoming a widely accepted therapeutic option (1-3).

Different surgical approaches have been described for this operation, either open (sternotomy, thoracotomy) or minimal invasive ones (cervicotomy, video-assisted thoracoscopic surgery, VATS). Anyway, median sternotomy still represents the gold standard.

The use of robotic systems in the surgical field represented an important innovation for minimally invasive techniques, enabling to overcome limitations of standard approaches (4).

In 1999, Loulmet and Reichenspurner described the first application of a surgical robotic system, performing a coronary by-pass (5,6). Yoshino performed the first robotic thymectomy for a small thymoma in 2001 (7). Rea and Ashton both described in 2003 the first series of patients undergoing robotic thymectomy for MG, using the latter a right-sided approach with completion of the operation through the left side, while the former used only a left-side approach (8,9). In the following years, different authors described their results with robotic thymectomy both for thymic tumors and in cases of nonthymomatous myasthenia gravis (10-12). Analysis of literature data shows that robotic approach in thymectomy is a feasible and safe operation. In case of patients with MG, this technique shows encouraging long-term results. On the other side, in patients affected by early stage thymoma, the technical and oncological results seem promising, but there is the need of longer follow-up data (10,13).

Patient selection and workup

Main indications for robotic thymectomy are patients with MG and patients with early stage thymic tumors associated or not with MG.

During pre-operative evaluation, it is important to investigate whether there are symptoms or clinical signs

Figure 1 Patient during a left-side operation; on the right side is positioned the robotic cart.

that could be related to MG and to evaluate the serum titer of antibodies against acetylcholine-receptor. If negative, anti-MuSK (muscle specific receptor tyrosine kinase) antibodies should be tested; there is evidence that a positive serum titer of anti-MuSK Ab is predictive of a lesser effect of thymectomy on MG symptoms (14).

Anyway, neurological assessment prior to surgery should be always performed to evaluate presence of active or significant symptoms of MG or to optimize the medical treatment. Particularly, the levels of corticosteroids should be decreased, prior to surgery. The risk of post-operative respiratory failure may be reduced by preoperative intravenous immunoglobulin administration or plasmapheresis, particularly in patients with partially-controlled symptoms (15,16).

Regarding timing for surgery, there isn't a gold standard, but it seems that an early removal of the thymic gland may improve the remission rate (16). Age over 50 years or antibody-negative disease are relative contraindications to thymectomy in nonthymomatous MG (17,18).

Moreover, all patients should be evaluated with a contrast-enhanced CT scan of the chest. Magnetic resonance and/or PET-CT scan can also be performed in the suspicion of thymoma or to distinguish between a thymic hyperplasia and a small thymoma.

Pre-operative chest X-rays should be performed to evaluate signs of extensive adhesions, related to prior pleuritis or thoracic surgical procedure, which may preclude a robotic approach.

Functional assessment should be completed with pulmonary function tests, complete blood examination and electrocardiogram.

Pre-operative preparation

The operation is performed under general anesthesia and the patient is ventilated through a double-lumen endotracheal tube. During procedure, patients are monitored by ECG, arterial line, pulse oximeter and urine output.

The patient is placed left or right-side up (based the side of operation), at a 30-degree angle with a bean bag. In left-sided approaches, the left arm is placed parallel to the bed while the right arm is positioned along the body to expose the axillary region (opposite for right-side operations). In the operating room the surgeon console is positioned away from the patient while the video column is at the bottom of the bed. The cart with the robotic arms is positioned on the right side of the bed at a 45° angle (opposite for right-sided approach) (*Figure 1*).

Because of the risks of an emergency conversion, the operative field should always be draped for an eventual median sternotomy.

Equipment preferences and cards

The most widespread surgical robot is the Da Vinci system (Intuitive Surgical, California, USA).

The Da Vinci system consists of a console where the surgeon sits while operating, connected to a patient-side cart with three interactive arms and a vision system (*Figure 2*).

The vision system is composed of a high definition touch-screen monitor, to allow the view of the operative field by the room staff, the video control systems and is connected to the two-channel endoscopic camera. The images captured by the 12-mm optic camera (0°–30°) are transferred to the console where the computer creates a virtual 3-D image of the operative field.

In the cart, there is also place for the CO_2-supply system and its intracavitary regulation.

The patient-side cart is equipped with three robotic arms, the central one holding the camera whereas the other two are connected to the surgical instruments. The left arm is generally connected with an atraumatic grasper instrument and the right arm is equipped with a monopolar cautery or an ultrasound dissector. The surgical instruments are designed to articulate with the main arm with seven degrees of motion and a 360° rotation, which is superior to the dexterity of human hand.

The surgeon sits at the console far from the patient and through a binocular localized in the upper part of the

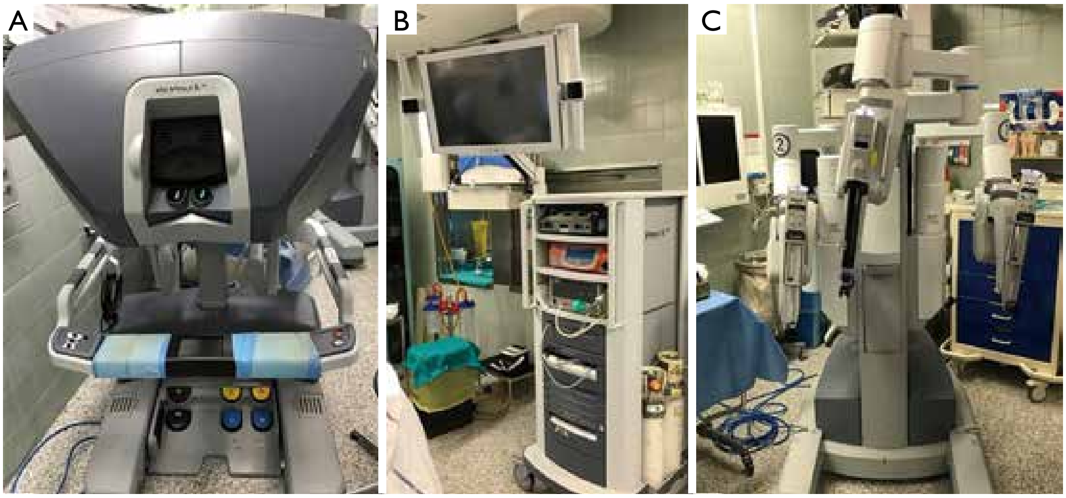

Figure 2 Components of the robotic system. (A) Surgeon's master console; (B) cart with vision system and CO_2-supply system; (C) operating cart equipped with robotic arms.

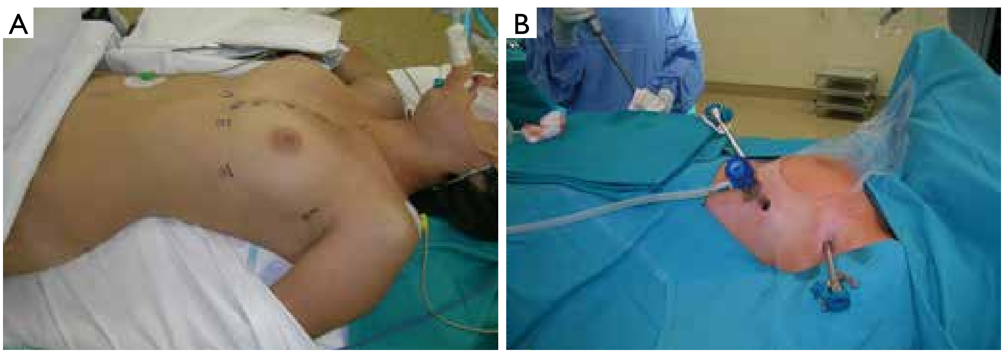

Figure 3 Preoperative patient's positioning and trocars' placement. (A) Patient positioned at a 30-degree angle, with marked landmarks and ports' insertion sites; (B) ports positioned: two ports for the robotic arms laterally and camera-port with CO_2-connecting line in the middle.

console he is able to see a 3D image of the operative field.

The surgeon's fingers grasp the master controls below the display and the robotic system allows the surgeon's hands and fingers movements to be translated into identical, precise movements of the instruments inside the patient's body. Moreover, the system filters the physiological hands' tremor, allowing extremely precise movements.

Procedure

Through an incision on the fifth intercostal space on the anterior/midaxillary line, a 12 mm port for the 3-D camera is introduced. Then other two incisions are performed, one on the midaxillary region on the third intercostal space and another on the parasternal space on the fifth intercostal space and two 8 mm thoracic ports are inserted (*Figure 3A*). The arms of the robotic system are then connected to the ports (*Figure 3B*). After placing the first port, it is advantageous to use the camera to help placing the other two ports, so that their trajectory line is correct and to avoid lesion of the heart or pericardium when placing the parasternal port.

CO_2 is inflated in the hemithorax through the camera port (pressure range 6–10 mmHg) to achieve a clear view within the pleural cavity and, enlarging the mediastinal space, it allows an easier dissection.

To exclude any pleural lesion in case of thymic tumors, is mandatory to perform a careful exploration of the pleural space before beginning the operation.

The surgical field is delimited by a triangle area with the lateral borders represented by the left or right phrenic nerves posteriorly and the mammary vessels anteriorly, the basis by the pericardium and with the apex situated at the base of the neck (*Figure 4*).

In case of left-sided approach, the dissection begins at the level of the left pericardiophrenic angle and moves upwards following the anterior border of the phrenic nerve, until all the mediastinal tissue is isolated from the nerve (*Figure 5A*). Caution must be paid not to damage the nerve, therefore during dissection it may be useful if the table-site assistant puts a hand on the patient abdomen to perceive any hemidiaphragm contraction. Subsequently, the thymic gland is dissected from the posterior aspect of the sternum until the right pleura is found and the right inferior horn is dissected (*Figure 5B*). The thymus is then mobilized upwards and separated from the pericardium, up the level of aortic arch (*Figure 5C*). In the superior part of the mediastinum, the pleura is opened between the phrenic nerve and the mammary vessels (*Figure 5D*). The dissection continues towards the base of the neck until the superior horns are found and separated by a blunt dissection from the inferior part of the thyroid (*Figure 6*). The superior horns are grasped and pulled downwards, the innominate vein is identified and dissected along its upper border, identifying, clipping and dividing the thymic veins (*Figure 7*).

When all the thymic tissue, the mediastinal and fat tissue are radically dissected, the resected specimen (*Figure 8*)

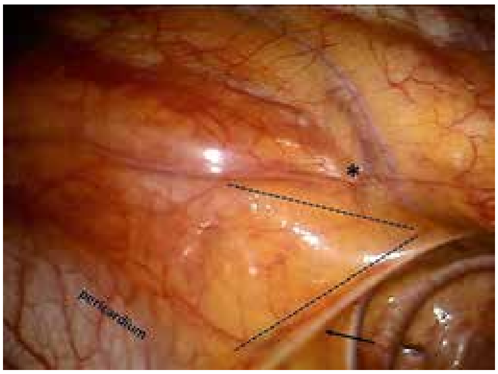

Figure 4 Surgical field individuated in a triangle area within the left phrenic nerve (arrow) and the mammary vessels (*).

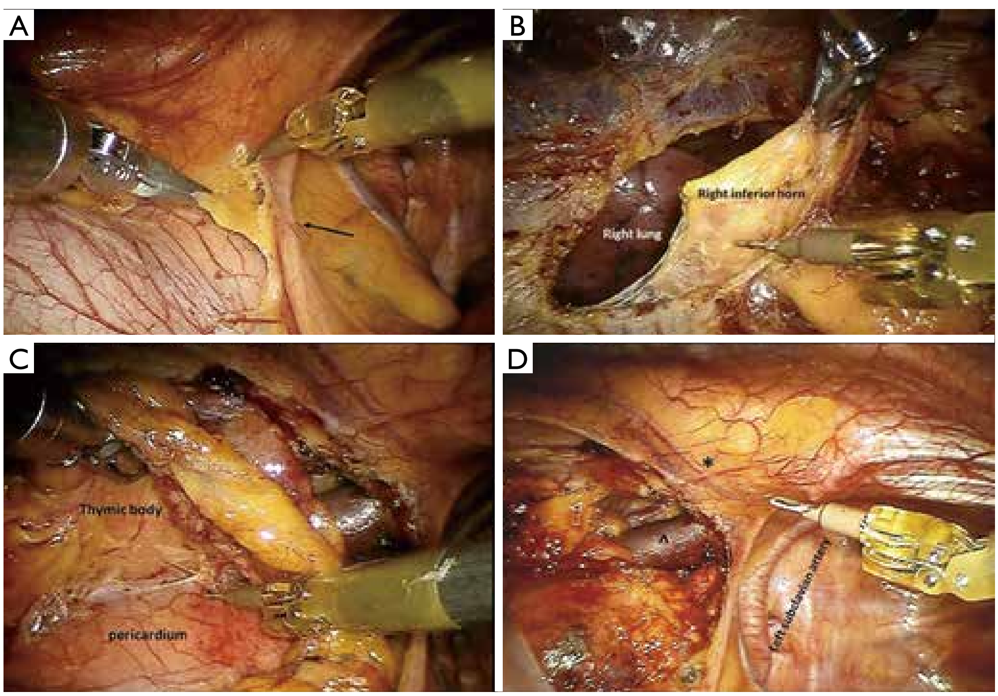

Figure 5 Surgical technique. (A) Dissection along the phrenic nerve; (B) dissection of the right inferior horn, with opening the right pleura; (C) division of the thymus from the pericardium; (D) dissection towards to the neck between the mammary vessels and the phrenic nerve (*, mammary vessels; ^, left subclavian vein; arrow, phrenic nerve).

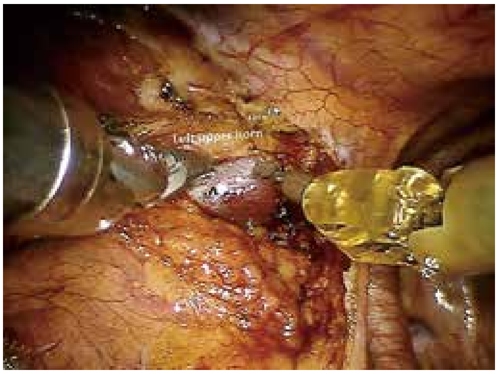

Figure 6 Dissection of the left upper horn of the thymus above the left subclavian vein (^).

Figure 7 Dissection and clipping of a thymic vein (^, left subclavian vein; arrow, thymic vein).

Figure 8 Thymic specimen.

is placed in an endoscopic bag and removed through the medial trocar incision.

In case of a right-sided operation, dissection starts from the cardiophrenic angle and then moves upwards with the mediastinal pleura incised following the right phrenic nerve, until all anterior mediastinum is separated from the nerve. At this point the pleura is incised along the right internal mammary artery and veins, from where the vessels originate all the way down to the diaphragm, dividing the mediastinal tissue from the sternum. The next step involves the dissection of the thymus from the pericardium, beginning down at the level of the inferior horns and moving upwards where the left innominate vein is identified. The thymus is separated from the brachiocephalic vein and the thymic veins are sequentially clipped and divided. The superior horns are then bluntly dissected from the inferior portion of the thyroid. To identify the phrenic nerve on the left side, the left mediastinal pleura is then opened and then the dissection of the gland is finished.

After controlling hemostasis, a chest tube is positioned through the medial port, the lung is inflated, and the other incisions are closed.

Role of team members

Surgical team should be composed by at least 2 surgeons, 1 anesthesiologist, 1 scrub nurse and 1 operating room nurse. One surgeon is at the robotic console, controlling the robot. The other is the table-site surgeon that must perform the incisions and introduce the ports. Moreover, he must be able to perform the connection between the robot and the ports and to rapidly undock the system and perform an emergency sternotomy in case of uncontrollable vascular bleeding or any other complication. The scrub nurse must be trained in the use of robotic material and able to exchange the robotic instruments. Operating room staff must be educated on the electronics needed for robotic surgery and how to connect and calibrate the robotic system components, and solve any technical problems that may arise during procedures.

Members of the robotic surgical staff must be familiar with the da Vinci system components, as well as how to problem-solve in the event of mechanical or electrical failure.

The anesthesiologist should be experienced in the management of patients undergoing thoracic procedures and of patient with MG. Frequent matter of concern may be represented by encroachment of the anesthesia workspace by the robot and difficulty in accessing the patient intra-operatively, therefore it is required a careful arrangement of the instrumentation and room organization.

Post-operative management

If possible, extubation is performed in the operating room and then the patient may then return to the surgical thoracic ward. In some cases, depending on the anesthesiologist's evaluation (i.e., patients with myasthenia gravis not well controlled pre-operatively) the patient can be transferred to the ICU for monitoring.

If the chest X-ray performed after operation doesn't shows any pathological findings and the quantity of fluid from the chest drain is permissive, the chest tube is removed generally 24 hours after operation and the patient is discharged 48–72 hours after surgery.

Tips, tricks and pitfalls

Different issues regarding robotic thymectomy are still matter of debate.

First is the choice of the side to perform the operation. The choice may be guided by anatomic analysis over the anatomy of the patient's thymus, considerations over the safety of trocars placement and based on the surgeons' preference (19).

Authors supporting a left-sided thymectomy base their choice on the observation that the left lobe is usually bigger and extended to the cardiophrenic region, and that region below the left innominate vein and the aortopulmonary window and are frequently sites of ectopic thymus. Common possible findings are a thymic gland that extends under or lateral to the left phrenic nerve, or descends posteriorly to the brachiocephalic vein (19). Another critical point is represented by the position of the right phrenic nerve that is partially protected by the superior vena cava and may be easily identified in the lower part of the mediastinum (20,21).

Other authors prefer a right-sided thymectomy, describing an easier learning curve with this kind of approach, mainly because of a better ergonomic position to accomplish dissection and a larger operative field, due to the absence of the heart, but also an optimal visualization of the venous confluence and of the aortocaval groove (19,22,23).

Anyway, the choice of the approach should be based on the patient's distribution of the thymic tissue, to perform a complete removal of the thymus and of all the mediastinal tissue. This is particularly important in patients with MG to obtain improvement or remission of the neurological symptoms, as the mediastinal fat is frequent site of ectopic foci of thymic tissue (24).

A particular care should be used when left innominate vein is dissected in order to avoid a major bleeding: when a small thymic vein is encountered and clipped, it is mandatory to search for a second vein that usually is present at the level of left innominate/superior vena cava angle. In about 5% to 10% of cases an anatomical variation is present: the most common is the upper left horn running behind the innominate vein and over the subclavian or carotid artery. In case of right-sided approach, the dissection of the abnormally positioned left upper horn may be demanding.

Another important point is the application of the robotic technique in patients with early stage thymoma. Historically, clinicians have been averse to use minimally invasive techniques for thymic tumors, both because of the supposed risk of rupture of the tumors' capsule during the manipulation of the lesion with the endoscopic instruments and the possibility of reduced safety margins with an increased probability of local recurrence (25-27).

Anyway, different studies demonstrated that robotic thymectomy for early stage thymomas is a promising technique with good results both from the surgical and oncological point of views (10).

Correct selection of patients is mandatory in case of thymomas, in order to avoid complications and achieve the best result from the oncological point of view.

Some radiological criteria have been identified to guide in the selection of the better patients to propose for minimal invasive thymectomy: the tumor location in the anterior mediastinum and its encapsulation, the presence between the thymoma and the other structures of a fat plane, the absence of compression on the surrounding structures, the tumor extending on one side and the presence of normal thymic tissue (28).

It is also still matter of debate the proper size of thymomas for robotic operations. The majority of the authors consider acceptable lesions smaller than 5 cm (21,25). Larger tumor's dimension, while not being an absolute contraindication, could make manipulation more difficult and interfere with the thoracoscopic procedure, prolonging the operative time, increasing the chance of an open conversion and the risks of tumor's rupture and spreading (21).

Because of the increasing popularity of minimally invasive techniques, the ITMIG recently proposed some standard policies regarding thymectomy. According to common surgical oncologic principles, thymomas must be always removed together with the surrounding normal thymus and fat, in order to obtain adequate safety margins, also for capsulated tumors. Moreover, it should be used a "no-touch" technique, where the unharmed thymic tissue and perithymic fat should be used for grasping and tractioning the tumor, avoiding the rupture of the capsule and the risk of pleural implantation (29). This technique is clearly a more complicated operation because of the need of a more accurate dissection, has a prolonged learning curve with delayed operative time compared to open techniques (21).

Certainly, open conversion is mandatory if, during a minimally invasive operation, the surgeon identifies any risk for the patient or any possible violation of the oncological principles.

Robotic surgery has some major disadvantages. This type of operation is known to be highly expensive, considering the costs of the robot itself, that may be limited by the multidisciplinary use of the robot, but also the costs for the annual maintenance and of the expensive disposable robotic instruments (11,30).

Moreover, there could be an increase in the risk of damaging delicate structures because of the absence of tactile feedback. Anyway, the superior view gained by the 3-D vision seems to overcome this disadvantage (21,31).

Finally, another disadvantage is represented by the placement of the surgeon, operating at a non-sterile console away from the patient (12,31). Thus, the sterile surgeon near the robot should be able to perform alone an emergency conversion. However, this emergency procedure could be made more difficult because of the time needed for the undocking of the robotic system.

Conclusions

Nowadays, robotic thymectomy is a proven technique in many centers. Available data show that it is a feasible and safe operation, with effective and encouraging long-term results in patients with non-thymomatous myasthenia and promising outcomes both from the oncological and surgical point of view in patients affected by thymoma. Through enhanced vision and high dexterity of instruments' movements it permits a safe and complete dissection of the thymic tissue, superior to standard thoracoscopic techniques. Robotic thymectomy is set to become the standard technique for thymectomy in patient affected by early stage thymomas and myasthenia gravis.

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Footnote

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

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Robotic subxiphoid thymectomy

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Abstract: When endoscopic surgery is indicated for myasthenia gravis and thymomas, most institutions use a lateral thoracic approach that includes robot-assisted surgery. However, with the unilateral thoracic approach, it can be difficult to ensure the operative field in the neck and difficult to identify the location of the contralateral phrenic nerve. In 2015, we reported on a robotic subxiphoid thymectomy (RST) in which the camera is inserted from the subxiphoid incision and robotic forceps are inserted from the bilateral intercostal spaces. With this approach, a camera is inserted into a subxiphoid incision which is the midline of the body and a surgical field comparable to that in a median sternotomy can be achieved. This makes it easier to identify the location of the bilateral phrenic nerves and offer the good visualization in the neck area. Here we report on our RST techniques. For a thymectomy without suturing, a subxiphoid, single-port thymectomy is performed because it is minimally invasive. In patients who require suturing, such as with a pericardial patch closure, RST is selected. The RST has excellent operability when performed with a robot, making it suitable for more difficult procedures. In the future, we believe that a robot-assisted thymectomy might become the standard method.

Keywords: Thymectomy; subxiphoid; thoracoscopy/VATS; robot

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Introduction

When endoscopic surgery is indicated for myasthenia gravis and thymomas, most institutions use a lateral thoracic approach that includes robot-assisted surgery (1-3). However, with the unilateral thoracic approach, it can be difficult to ensure the operative field in the neck and difficult to identify the location of the contralateral phrenic nerve. Previously, we reported on a single-port thymectomy using a subxiphoid approach to extract the thymus from a single subxiphoid incision (4). The operative field from the camera inserted through the midline of the body made it easy to verify the neck area and identify the location of the bilateral phrenic nerves. However, a shortcoming of this approach is operability. With surgery through a single incision, there is interference between the camera scope and the forceps in the surgeon's hands, making it difficult to perform more complex procedures such as suturing operations.

In 2003, a robot-assisted surgery for myasthenia gravis and anterior mediastinal tumors was reported (5), and in recent years good outcomes with such surgery have been reported (6). However, these robot-assisted surgical techniques use a lateral thoracic approach (7). Even with the use of a robot, the lateral thoracic approach makes it difficult to gain a good operative field of the neck and to identify the location of the contralateral phrenic nerve. Furthermore, to adequately exert the performance of the robot system, the target, i.e., the thymus, should be between the left and right arms of the robot; however, with the lateral thoracic approach, the neck portion of the thymus is not between the left and right arms. In 2015, we reported on a robotic subxiphoid thymectomy (RST) (*Figure 1*) (8). With this approach, a camera is inserted into a subxiphoid incision which is the midline of the body and a surgical field comparable to that in a median sternotomy can be achieved. This makes it easier to identify the location of the

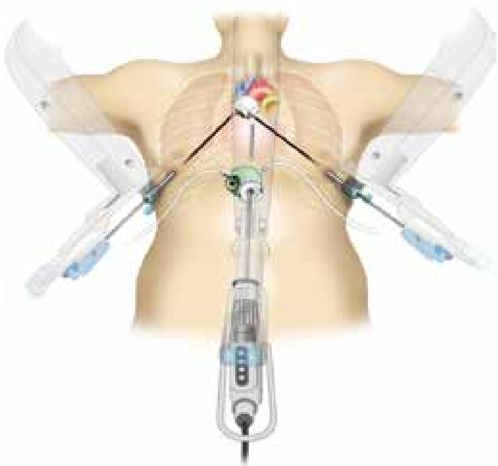

Figure 1 Robotic subxiphoid thymectomy (RST). A pericardial resection and substitution with an artificial pericardial sheet are very easy with an articulated robotic system.

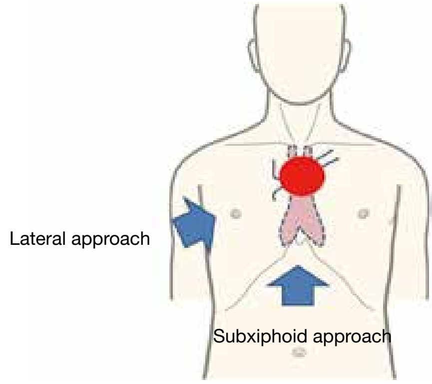

Figure 3 When the tumor is close to the brachiocephalic vein, the approach from the lateral chest cannot identify the contralateral brachiocephalic vein beyond the tumor (Lateral approach). In contrast, with the subxiphoid approach, the left brachiocephalic vein may be identified at proximal and distal ends to the tumor (Subxiphoid approach).

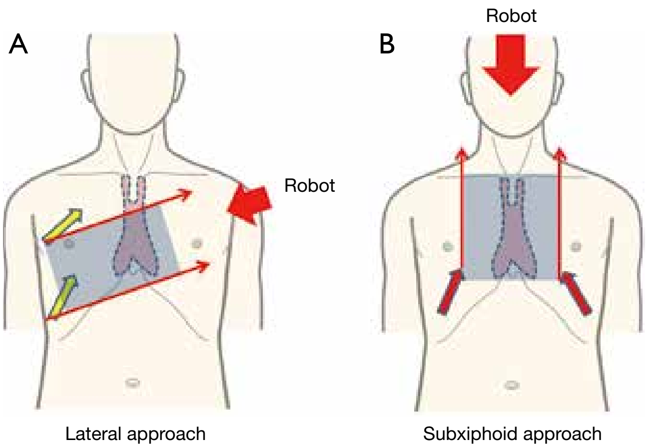

Figure 2 With the approach from the lateral thoracic side, the neck portion of the thymus is not between the left and right arms (A). In contrast, with the subxiphoid approach, the entire thymus is between the left and right arms, thereby enabling good robotic operability (B) (9).

bilateral phrenic nerves and offer the good visualization in the neck area. Furthermore, with this approach, the left and right robot arms are inserted in the 6th intercostal space of the bilateral precordium and the entire target/thymus lies between the left and right arms, thereby enabling maximum robot performance (*Figure 2*) (9). In the event of suspected invasion into the left brachiocephalic vein, to perform the surgery safely, taping of the left brachiocephalic vein distal and proximal to the tumor is needed. However, with robot-assisted surgery using a lateral thoracic approach, the presence of a tumor makes it difficult to identify the contralateral left brachiocephalic vein. In contrast, with RST, the entire left brachiocephalic vein can be observed through a midline incision, and the left brachiocephalic vein may be taped distally and proximally to the tumor (*Figure 3*). Furthermore, in the event of tumor invasion into the pericardium, an endoscopic pericardial incision and patch closure with a pericardial sheet is a highly difficult procedure when performed endoscopically with human hands; however, if the robot-assisted system with articulated forceps is used, it is very easy (9). In cases where the left brachiocephalic vein is taped distally and proximally to the tumor, or a concurrent pericardial resection and reconstruction is required, it is generally highly likely that endoscopic surgery will not be indicated; however, if a robot is used they can become minimally invasive procedures. As robot-assisted surgery is expensive, the benefits to the patient should balance the high cost. In general, we indicate robot-assisted surgery for highly complicated procedures that are difficult for human hands to perform endoscopically. RST helps secure the operative field of the neck and facilitates the identification of the location of the bilateral phrenic nerves. Furthermore, it has excellent operability when performed with a robot, making it suitable for more difficult procedures. In the future, we believe that a robot-assisted thymectomy might become the standard

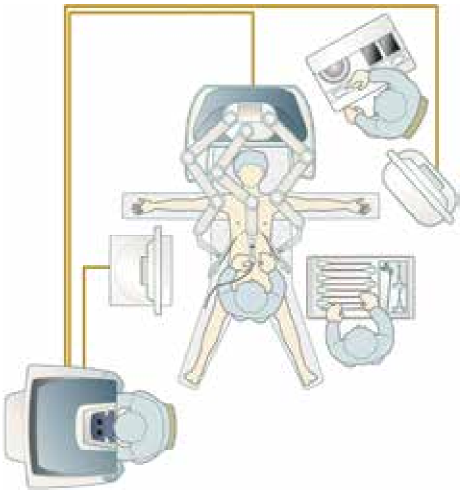

Figure 4 Equipment configuration with the da Vinci SI surgical system.

method. Here we report on our RST technique.

Patient selection

For a thymectomy without suturing, a subxiphoid, single-port thymectomy is performed because it is minimally invasive. In patients who require suturing, such as with a pericardial patch closure, dual-port thymectomy with an additional port placed in the right 5th intercostal space along with a subxiphoid single-port thymectomy (10) or RST is selected.

Pre-operative preparation

The patient is placed in the supine position. The arms are open so as not to be hit by the robot arms. The configuration of the equipment when using the da Vinci SI surgical system (Intuitive Surgical, Sunnyvale, CA, USA) is shown in *Figure 4*.

Equipment preference card

We use the da Vinci SI surgical systems, which are capable of using vessel sealers as the vessel-sealing system. We use the GelPOINT Mini (Applied Medical, Rancho Santa Margarita, CA, USA) as the port for a single-port surgery. The GelPOINT Mini has a gel seal on the port platform, which prevents over-fixation of the mini-ports and decreases interference of the instruments once inserted. It also enables of CO_2 insufflation. The surgeon performs a pre-docking procedure using the vessel-sealing device. There are various types of vessel-sealing devices; however the LigaSure™ Maryland Jaw 37 cm (Covidien, Mansfield, MA, USA) device with a dissecting shaped tip is suitable for this surgery.

Forceps mounted on the robotic arms include Cadiere forceps or fenestrated grasping forceps attached to the bipolar vessel-sealing device on the left hand arm, and Maryland forceps attached to the bipolar vessel-sealing device or spatula attached to a monopolar vessel-sealing device on the right hand arm. A needle holder is used when suturing. The da Vinci surgical system can use four arms; however, to decrease the number of incisions, we do not use the 4th arm.

Procedure

Pre-docking procedure

Under general anesthesia, artificial ventilation is performed using a double-lumen endotracheal intubation tube. The surgeon performs the surgery standing between the legs of the patient, while the scopist stands to the right of the patient to operate the thoracoscope. To begin with, a 3-cm transverse incision is made 1 cm below the xiphoid process, and the rectus abdominis is dissected at its attachment to the xiphoid process. The posterior aspect of the sternum is blindly detached using the finger. A 5-mm vertical incision is made on the fascia of the rectus abdominis, the GelPOINT Mini-port for a single-port surgery is inserted into the subxiphoid incision and CO_2 insufflation is performed at 8 mmHg. Using a rigid scope of 5 mm in diameter with 30° oblique view and using a LigaSure™ Maryland type device, the thymus is detached from the posterior aspect of the sternum. An incision is made into the bilateral mediastinal pleura and the thoracic cavity is exposed bilaterally. Next, 1-cm skin incisions are made on either side in the 6th intercostal space along the anterior axillary line of the precordium, and a port used for the da Vinci robotic surgery is inserted (*Figure 5*).

RST

When using the da Vinci SI surgical system, the system is docked from the cranial side (*Figure 4*). A port used for a 12-mm camera is inserted into the subxiphoid port for a single-port surgery and attached to the da Vinci camera

Figure 5 Pre-docking procedure (11).
Available online: http://www.asvide.com/articles/1039

Figure 6 Robotic subxiphoid thymectomy (RST) (12).
Available online: http://www.asvide.com/articles/1040

Figure 7 Robotic pericardial patch closure by the subxiphoid approach (13).
Available online: http://www.asvide.com/articles/1041

scope. The da Vinci arms are then attached to the bilateral ports in the 6^{th} intercostal space along the anterior axillary line of the precordium. The camera scope is used changing opportunely from direct-forward viewing to a 30° oblique viewing. At times, the assistant will expand the surgical field by pulling the thymus using an Autonomy Grasper 45 cm (Cambridge Endo, Framingham, MA, USA), which are forceps for single-port surgery, or a SILS™ Hand Instrument SILS Clinch 36 cm (Covidien, Mansfield, MA, USA). The thymic vein is dissected using an EndoWrist Vessel Sealer (Intuitive Surgical, Sunnyvale, CA, USA). The thymus and thymoma are placed in a pouch inside the mediastinum and extracted via the subxiphoid incision. A 20-Fr drain is inserted through the subxiphoid incision into the mediastinum (*Figure 6*).

In the event of a suspected tumor infiltration of the lungs, a stapler is inserted through the subxiphoid port or the bilateral lateral thoracic ports, and a partial lung resection is performed. In recent years, it has become possible to attach a stapler to the da Vinci surgical system. An articulated stapler will facilitate surgery in a narrow mediastinum and thoracic cavity. In the event that pericardial invasion is suspected and a pericardial patch closure is performed, the incision is performed after the pericardium has been adequately detached from the tumor, and the pericardium is dissected using the EndoWrist Vessel Sealer. The defective portion of the pericardium is closed by a patch using a Gor-tex pericardial sheet with 3–0 Vicryl interrupted sutures (*Figure 1*). The interrupted sutures can be easily performed using the articulated robotic forceps (*Figure 7*).

Role of team members

For a safe robotic surgery, procedures must be performed by a surgical team consisting of a surgeon, anesthesiologist, engineer, and nurse, all of whom must be well-skilled in robotic surgery. When performing a new surgery, the entire team must meet in advance to perform a simulation.

Tips, tricks, and pitfalls

When using the da Vinci SI surgical system, the robot is docked from the cranial side. At this point in time, the authors have no experience in this approach using the daVinci Xi system. However, with the da Vinci Xi system the robotic arms are mounted on the ceiling and therefore docking can be performed from the lateral side of the patient. If docking from the lateral side of the patient can be performed, the robot does not lie over the patient's head, ensuring that a space is available near the head of the patient for the anesthesiologist.

For the endotracheal intubation tube, if there is no lung invasion, a single-lumen tube can be used. However, if there is suspected tumor invasion of the lungs, a double-lumen tube is chosen to enable differential lung ventilation. When establishing artificial ventilation, pressure control ventilation delivered at the minimal intratracheal pressure is used to ensure sufficient ventilation. PEEP is not used as it inflates the lungs and disturbs the operative field. CO_2 insufflation in the mediastinum at 8 mmHg provides a good operative field by maintaining lung ventilation and eliminating pressure moderately on the bilateral lungs.

In CO_2 insufflation, when using suction, the supplied CO_2 is aspired, which inflates the lungs and worsens the surgical operative field. As an alternative to suction, a gauze roll should be placed in the mediastinum to wipe up blood as required. The AirSeal system (SurgiQuest, Milford, CT, USA) is a CO_2 insufflation system with which suction can be used, and thus might be useful for robotic surgery.

In the event that pulling the thymus is desired to enlarge the operative field, the assistant does so by inserting forceps with an articulated tip through the subxiphoid port; however, if this is difficult to do, then an additional port can be placed on the lateral chest. Although we do not use this practice, if necessary, a 4th robotic arm may be used.

Acknowledgements

None.

Footnote

Conflicts of Interest: The author has no conflicts of interest to declare.

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Multi-institutional European experience of robotic thymectomy for thymoma

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Background: Robotic thymectomy for early-stage thymomas has been recently suggested as a technically sound and safe approach. However, due to a lack of data on long term results, controversy still exists regarding its oncological efficacy. In this multi-institutional series collected from four European Centres with high volumes of robotic procedures, we evaluate the results after robot-assisted thoracoscopic thymectomy for thymoma.

Methods: Between 2002 and 2014, 134 patients (61 males and 73 females, median age 59 years) with a clinical diagnosis of thymoma were operated on using a left-sided (38%), right-sided (59.8%) or bilateral (2.2%) robotic approach. Seventy (52%) patients had associated myasthenia gravis (MG).

Results: The average operative time was 146 minutes (range, 60-353 minutes). Twelve (8.9%) patients needed open conversion: in one case, a standard thoracoscopy was performed after robotic system breakdown, and in six cases, an additional access was required. Neither vascular and nerve injuries, nor perioperative mortality occurred. A total of 23 (17.1%) patients experienced postoperative complications. Median hospital stay was 4 days (range, 2–35 days). Mean diameter of resected tumors was 4.4 cm (range, 1–10 cm), Masaoka stage was I in 46 (34.4%) patients, II in 71 (52.9%), III in 11 (8.3%) and IVa/b in 6 (4.4%) cases. At last follow up, 131 patients were alive, three died (all from non-thymoma related causes) with a 5-year survival rate of 97%. One (0.7%) patient experienced a pleural recurrence.

Conclusions: Our data suggest that robotic thymectomy for thymoma is a technically feasible and safe procedure with low complication rates and short hospital stays. Oncological outcome appears to be good, particularly for early-stage tumors, but a longer follow-up period and more cases are necessary in order to consider this as a standard approach. Indications for robotic thymectomy for stage III or IVa thymomas are rare and should be carefully evaluated.

Keywords: Thymoma; robotic thymectomy; early stage thymoma; myasthenia gravis (MG); thoracoscopy

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Introduction

Radical thymectomy is the gold standard treatment for resectable thymomas, with completeness of resection representing the most important prognostic factor (1). Currently, median sternotomy is widely considered as the standard approach for thymoma resection at any stage, allowing a technically easy and oncologically safe operation (2). While the video-assisted thoracoscopic surgery (VATS) approach has been extensively used for mediastinal diseases in the last three decades, it was mainly confined to the treatment of several benign diseases or to thymectomy in cases of non-thymomatous myasthenia gravis (MG) (3-5). The first VATS approach for thymoma was described in early 1990s (6); since then, only few authors have published small series of VATS thymoma resections with short-term follow-up, leading to a paucity of clear and sound data about the effectiveness of this approach (2,7-9). Consequently, a number of surgeons are still reluctant to use this surgical approach that remains controversial—the supposed increased risk of local recurrence (due to reduced safety margins after minimally invasive resection) and the possible rupture of the capsule with implantation of the tumor during endoscopic manipulations are the most common arguments against the VATS approach. Furthermore, the lack of long-term oncologic results, the learning curve required to perform this operation safely and the relative rarity of this tumor are additional reasons that slow the adoption of the VATS resection for early stage thymomas (10). The introduction of robotic-assisted technologies in the late 1990s provided a technical advancement able to overcome the limitations of conventional thoracoscopy. Specifically, the three-dimensional vision system and the articulated instruments of the da Vinci Surgical Robotic System (Intuitive Surgical, Inc., Sunnyvale, CA, USA) allow for an intuitive, 'open-like' intervention, but with minimally invasive access. The application of robotic technology has been tested in a variety of thoracic surgery procedures, particularly for mediastinal diseases, where the robotic system is thought to provide the maximum benefit (11,12). The aim of this study was to evaluate the safety and the feasibility of robotic thymectomy, analysing the oncologic outcome in a group of patients with clinically defined early-stage thymoma, in four European Centres with extensive experience in this type of operation.

Materials and methods

We reviewed the data of 134 patients undergoing robotic thymectomy for clinically defined early-stage thymoma (Masaoka stages I and II) collected between 2002 and 2014 by four European Thoracic Surgery Centres (University of Maastricht-Nederland; University of Padova-Italy; University of Pisa-Italy; University of Innsbruck-Austria). All patients signed a detailed consent form in which they were informed about possible complications of a thymoma resection with robotic approach and the lack of long-term data. The institutional review board of each centre approved the study. Information on patient demographics, presence of associated MG, tumor characteristics, stage, intra and postoperative data (e.g., complications, need for open conversion or additional ports or accesses, operative time, length of hospital stay) were collected. The Masaoka staging system was used to assess the pathological stage (2), while the new World Health Organization classification was used for histological definition (13). The Myasthenia Gravis Foundation of America (MGFA) classification (14) was applied to stratify the preoperative class of MG. Preoperative assessments included evaluation of pulmonary and cardiac functions, total body computed tomography (CT) or magnetic resonance imaging (MRI). Preferred radiological characteristics to be eligible for robotic thymectomy were the location of the tumor in the anterior mediastinum, a distinct fat plane between the tumor and surrounding structures, unilateral tumor predominance, tumor encapsulation, existence of residual normal appearing thymic tissue, and no mass compression effect (*Figure 1*) (7). In cases of unexpected intraoperative finding of involvement of surrounding structures (Masaoka stage III), pleuro-pericardial or pulmonary nodules (Masaoka stage IVa/b), the robotic approach was converted to an open approach if the resection was considered technically difficult, unfeasible or unsafe for the patient. Patients were followed up until death or May 2015, if alive, by periodic visits (with neurologists if affected by MG) and phone contact. A total body CT scan was performed every six months for the first two years postoperatively, then every year. There were 61 (45.5%) males and 73 (54.5%) females, with a median age of 59 years (range, 14–88 years). Seventy (52.2%) patients were affected by MG.

Surgical technique

The side of surgical access was based on a single surgeon's experience, or occasionally on the presence of unilateral tumor predominance. The surgical technique of robotic thymectomy from either the left or right side has been described in existing literature (15,16). This procedure was performed differently from thymectomy for non-thymomatous patients, with all surgeons adopting a "no-touch technique" for an "en bloc" resection of thymus and perithymic fat tissue. In this technique, the thymoma was never touched and the normal thymic tissue and peri-thymic fat were used for grasping and for traction. This technique avoids a direct manipulation of the tumor, in order to minimize the risk of tumor seeding in consequence of capsule damage. All thymus and perithymic fat were dissected with safe surgical margins, according to the International Thymic Malignancy Interest Group criteria (17), and the

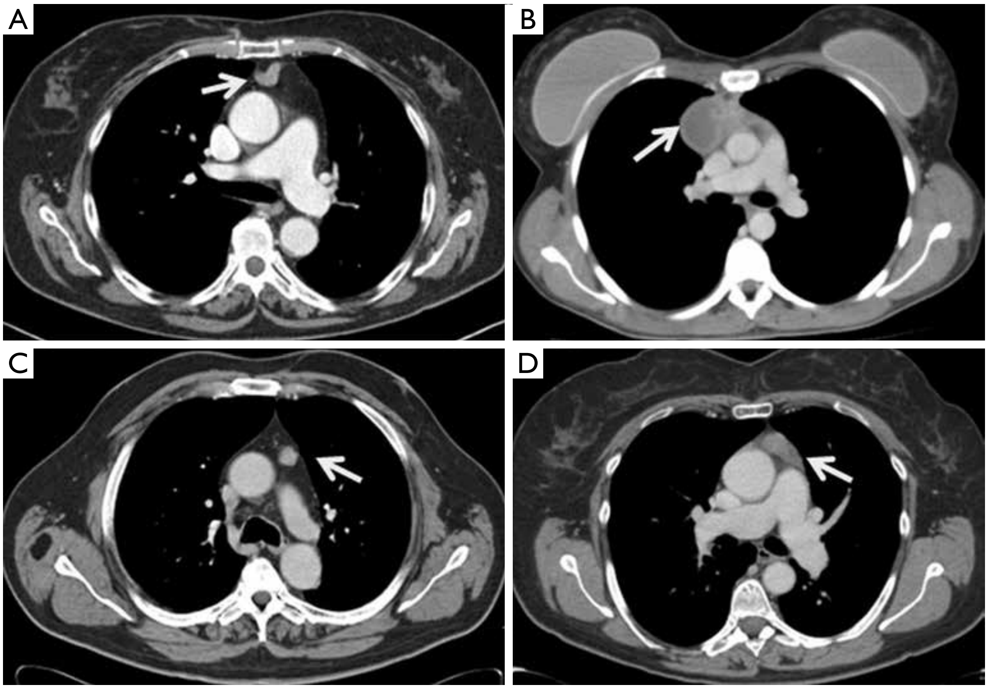

Figure 1 CT scans of: (A) small thymoma centrally located (white arrow) and surrounded by perithymic fatty tissue; (B) cystic thymoma (white arrow) with unilateral predominance on the right side; (C) small thymoma (white arrow) with unilateral left predominance and surrounded by perithymic fatty tissue; (D) thymoma (white arrow) with unilateral left predominance.

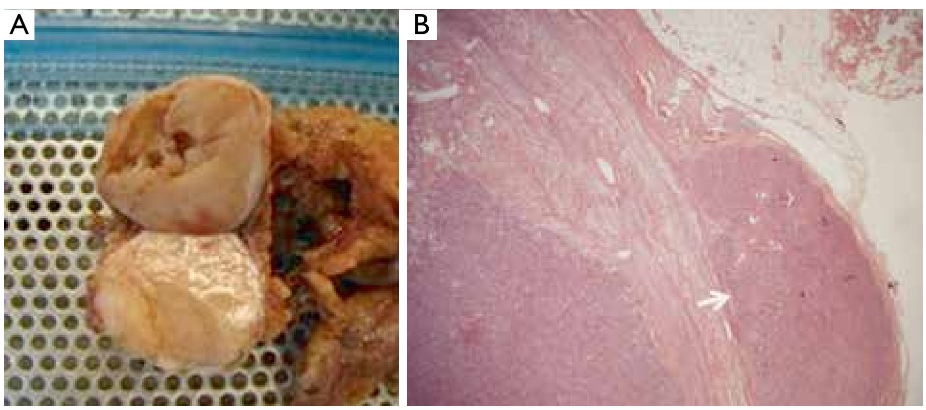

Figure 2 (A) Specimen of macroscopic encapsulated type AB thymoma in which (B) the pathological analysis revealed a microscopic capsular invasion (white arrow) (Haematoxylin-Eosin stain, original magnification ×25).

completeness of thymectomy was assessed by macroscopic inspection of the thymic bed, specimen and subsequent pathological analysis (*Figure 2*).

Statistical analysis

Data were expressed as absolute numbers, percentage, median or mean values ± standard deviation (SD). Survival curves were calculated by Kaplan-Meier method.

Results

The robotic approach was left-sided in 51 (38%), right-sided in 80 (59.8%) and bilateral in three (2.2%) patients. The median operative time was 140 minutes, ranging between 60 and 353 minutes (mean 146.4±43 minutes). Twelve (8.9%) patients needed conversion to an open approach (in two cases due to large diameter of tumor interfering with a safe dissection, in 10 cases for unexpected invasion of surrounding structures as the great vessels, lung or pleura-pericardial implants). In one (0.7%) case, a standard thoracoscopy was used after robotic system breakdown. In six (4.4%) cases, an additional access (cervicotomy in one case, an additional homolateral thoracoscopic port for suction purpose in five cases) was required. No vascular and nerve injuries were recorded, and no perioperative mortality occurred. A total of 23 (17.1%) patients had postoperative complications: four cases of atrial fibrillation, three cases of myasthenic crisis, three pneumothoraces after chest tube removal, three pleural effusions, two cases of pneumonia, one haemothorax treated conservatively by blood transfusion, one chylothorax, one orthostatic hypotension, one wound infection, one urinary tract infection treated with medical therapy, one pulmonary embolism, one mediastinal infection, and one pulmonary herniation. Median hospital stay was 4 days (range, 2–35 days; mean 4.8±2.5 days). Mean diameter of the resected tumors was 4.4±1.3 cm (range, 1–10 cm), Masaoka stage was I in 46 (34.4%), II in 71 (52.9%), III in 11 (8.3%), IVa in 5 (3.7%) and IVb in 1 (0.7%) patient. Histologic evaluation revealed 22 (16.4%) type A, 23 (17.2%) type AB, 23 (17.2%) type B1, 40 (29.8%) type B2, and 26 (19.4%) type B3 thymomas. At the last follow up (May 2015: median 42 months, range, 5–159 months; mean 48±35.7 months), 131 (97.8%) patients were alive, 3 (2.2%) patients died all for non-thymoma related causes (leukemia, vulval carcinoma and colon carcinoma). A pleural recurrence was found in 1 (0.7%) patient with original Masaoka stage IVa. The five-year overall survival rates were 97%, and the five-year thymoma-related survival rates were 100%.

Discussion

Since its introduction into clinical practice in the early 1990s, VATS has gained broad acceptance for diagnostic and therapeutic interventions for both pulmonary and mediastinal benign diseases (3-6). The main recognized advantages of VATS compared with open approaches are minimal operative trauma, lower morbidity, early improved pulmonary function, shorter hospital stays and better cosmetic results (3,4,18). These obvious advantages have increased the acceptability of the VATS approach, especially among patients with MG, leading to an increased number of thoracoscopic thymectomies being performed for non-thymomatous MG with good surgical and neurological results (15,16,19). Contrary to the lung cancer experience however, in which VATS resection has become the standard approach for early-stage NSCLC, most surgeons are still reluctant to perform a thoracoscopic thymectomy in patients with thymoma, due to technical and oncological concerns. There are a number of technical reasons to not use thoracoscopy: the upper mediastinum is a delicate and difficult-to-reach anatomical area with vulnerable large vessels and nerves, particularly with thoracoscopy. In the two-dimensional view of the operative field, the surgeon's tremor is enhanced by the thoracoscopic instruments and they do not articulate, making it difficult to operate in a fixed three-dimensional space such as the mediastinum. Moreover, thoracoscopic thymectomy is considered a technically challenging operation with a steep learning curve (10). The oncological concerns relate to the possible breach of tumor capsule with risk of tumor seeding locally or in the pleural cavity, and the difficult evaluation of resection margins with reduced oncological accuracy and safety. The robotic surgical system has provided several advantages able to overcome some technical and methodological limits of conventional thoracoscopy: (I) the improved dexterity of instruments (7 degrees of freedom articulation, 360 degrees of rotation) allows complex three-dimensional movements, providing a safe and comfortable dissection around vessels, nerves, and tiny and remote areas such as the superior horns or the contralateral mediastinum; (II) the high-resolution, three-dimensional vision permits the best possible and magnified view of the surgical field; and (III) the filtering of hand tremors allows greater technical precision. In our opinion, these characteristics have significantly increased the safety and the oncological effectiveness of robotic thymectomy for thymoma. In fact, there is less manipulation of the thymic and perithymic tissue during the operation, and a better evaluation of healthy tissue as a result of the high quality image. This allows for a more precise and low-risk dissection with wide safety margins, and reduced possibility of an incautious tumor breaching, incomplete resection or iatrogenic injury. The lack of tactile feedback could theoretically increase the risk of damaging tumor capsule; however, this disadvantage seems widely compensated by the superior three-dimensional vision control of the system. In the last 15 years, several authors have published the results of thoracoscopic and robotic thymectomy for early-stage

Table 1 Review of the published studies on thoracoscopic and robotic thymectomy for thymoma

Author	Patients (N)	SA	Masaoka stage I/II	TS (cm)	5-year survival (%)	FU (months)	RR (%)	OC (%)	OT (min)	POS (days)
Roviaro *et al*. (2)	22	uVATS	22	–	–	–	4.5	4.5	75*	6*
Cheng *et al*. (7)	44	uVATS	27/17	7.7*	100	34.6*	0	0	194*	7.6*
Odaka *et al*. (8)	22	uVATS	–	–	–	21.6*	0	0	194*	4.6*
Agasthian *et al*. (9)	50	uVATS	25/25	5*	100	58*	2	0	150*	5*
Pennathur *et al*. (20)	18	bVATS	5/13	3.5*	100	27**	0	0	–	2.9*
Takeo *et al*. (21)	34	bVATS	15/19	5.2*	100	65*	2.8	0	219*	10.5*
Kimura *et al*. (22)	45	uVATS	41/4	4.8*	100	–	6.7	0	197*	14*
Liu *et al*. (23)	76	uVATS	57/19	9.2*	100	61.9*	2.6	1.3	141.7*	7.1*
Ye *et al*. (24)	125	uVATS	80/45	3.2*	–	41**	0.8	3.2	170**	8**
Sakamaki *et al*. (25)	71	uVATS	40/31	3.5**	97	48**	1.4	5.6	–	–
Mussi *et al*. (26)	13	robotic	7/6	3.3*	100	14.5**	0	7.7	139*	4*
Marulli *et al*. (27)	79	robotic	30/49	3.7*	90	51.7*	1.3	1.3	165*	4.4*
Ye *et al*. (28)	23	robotic	21/2	2.9*	100	16.9*	0	0	97*	3.7*
Keijzers *et al*. (29)	37	robotic	20/13	5.1*	100	36**	2.7	13.5	149*	3**
Present series	134	robotic	46/71	4.4*	97	48*	0.7	8.9	146*	4**

SA, surgical access; bVATS, bilateral video-assisted thoracic surgery; uVATS, unilateral video-assisted thoracic surgery; TS, tumor size; FU, median follow-up; RR, recurrence rate; OC, open conversion; OT, operative time; POS, post-operative length of stay. *, mean value; **, median value.

thymoma (*Table 1*). The available data confirm that this approach may be considered technically sound and safe in the hands of appropriately-trained surgeons. However, data are still inconclusive with regard to oncological outcome due to the lack of long-term follow-up. In fact, thymomas are indolent tumors, and a long lapse of time (at least 10 years) is necessary to evaluate the survival and relapse rate. Therefore, as pointed out by Davenport *et al*. in a systematic review (30), there is a lack of evidence in the current literature supporting a minimally invasive approach compared to a standard transsternal approach. At that time, the open transsternal surgical approach is widely considered the gold standard for resection of thymoma, ensuring the best chance for a complete resection (1,2). However, despite the lack of long oncological follow-up, the surgical results are outstanding: no major complications or mortality occurred in this large series. Other authors adopting either the conventional VATS or robotic approach also reported similar results (2,3,7-9,20,22-29). In contrast to other authors supporting a thoracoscopic subtotal thymectomy for non-invasive thymoma without MG as the preferred resection modality regardless of tumor size and tumor capsule characteristics (8-19,30,31), our policy was to undertake an extended thymectomy in all cases, such as in the open approach. In the absence of definitive long-term data, a standardization of the technique is necessary in order to avoid biases in the evaluation of the outcome. Moreover, we consider the intraoperative manipulation of the specimen to be safer when the perithymic fat tissue is contextually resected 'en bloc'. Most of our patients (87.3%) had an early-stage tumor due to the selection criteria we adopted, based on the radiological criteria proposed by Cheng *et al*. (7): the location in the anterior mediastinum, tumor encapsulation, a distinct fat plane between the thymoma and vital organs, the existence of residual normal appearing thymic tissue, no mass compression effect and unilateral tumor predominance, particularly for tumors of dimension greater than 3 cm. However, while most cases were clinically diagnosed as Masaoka stage I, 52.9% patients were found to be Masaoka stage II, 8.3% were in stage III and 4.4% in stage IVa/b after resection and final histological evaluation. A similar finding was reported by Takeo *et al*. (21), where it was revealed that 57% of patients had Masaoka stage II and III after an initial clinical diagnosis of stage I, while in a report by Quintanilla-Martinez *et al*. (32), 28.5% of the tumor reported by the surgeon to be encapsulated

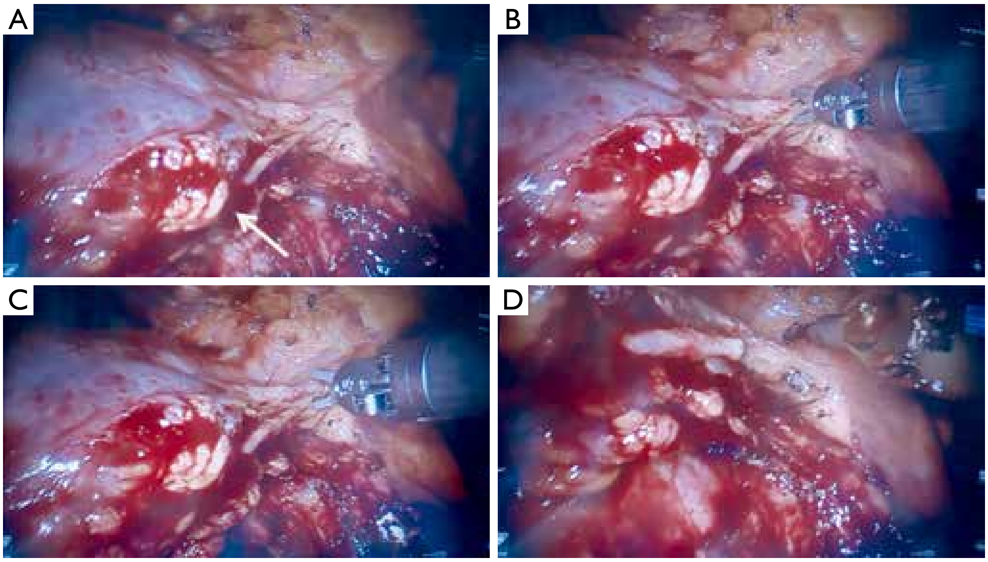

Figure 3 (A) Intraoperative left thoracoscopic view of thymoma invading the left phrenic nerve (white arrow) that is (B,C) doubly clipped and (D) sectioned by robotic instruments.

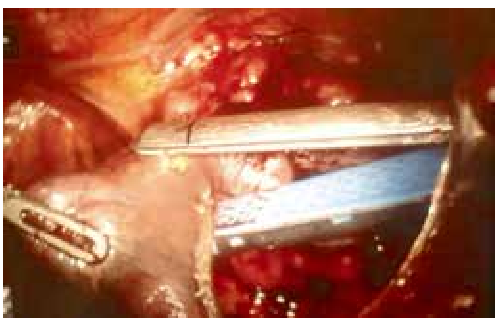

Figure 4 Intraoperative right thoracoscopic view of a thymoma invading the right lung, resected by wedge using an endoscopic stapler during a robotic procedure.

showed a microscopic evidence of capsular invasion. In regards to Masaoka stage III and IV discovered at surgical exploration, our policy was to convert to an open access (sternotomy or thoracotomy) based on individual surgeon's judgement. In particular, when the resection was considered unsafe or unfeasible by robotic approach, an open resection was performed; this occurred in 10 cases, while in the remaining seven cases, a resection extending to the pericardium, the phrenic nerve (*Figure 3*), lung (*Figure 4*) or parietal pleura were performed entirely by robotics. Despite being technically feasible, extended resections should be considered experimental and reserved to very select cases, as the oncological safety is still unknown. Another debated point is the appropriate size of thymoma for VATS or robotic resection; the majority of authors dealt with lesions smaller than 5 cm, but an average tumor diameter around 3 cm is generally considered as oncologically acceptable (10,27). In our experience, the mean diameter of resected lesions was 4.4 cm, with a range between 1 and 10 cm. A large tumor size was not considered an absolute contraindication; however it may interfere with the surgical procedure, making the manipulation more difficult with increased chance of an open conversion, prolonged operative time or capsule injury, as reported by Kimura *et al*. (22). In regards to the surgical results, no mortality, low morbidity and short hospital stay were observed. The operative times and open conversion rate were comparable with other series of thoracoscopic thymoma resection (*Table 1*). It is interesting to note that no conversions due to intraoperative vascular accidents were required, as the accurate vision allowed the surgeons to perform an optimal vascular dissection or identify early vascular invasion, avoiding any intraoperative damage. Looking at the oncologic outcome, a recurrence rate ranging between 0% and 6.7% has been reported in previous thoracoscopic and robotic series. In our experience, the single pleural relapse was observed in a Masaoka stage IVa despite a macroscopic radical intervention. Relapses also frequently occur in open surgery due to microscopic residual disease. Cheng *et al*. (33) and Pennathur *et al*. (20) compared the VATS and transsternal approaches for thymoma in small series, reporting no significant difference in recurrence rate and overall survival between the two groups. Although very encouraging, the oncological results need definitive validation, since the indolent nature of thymoma requires more mature data from longer follow-up. The present study has some limitations, particularly the non-randomized, retrospective and multi-institutional methodology. In addition, the follow-up period is still inadequate to allow a definitive conclusion on the oncological outcome.

In summary, robotic thymectomy for early stage thymoma is a technically safe and effective operation. In addition to the advantages of a minimally invasive approach (short hospital length of stay, excellent cosmetic results, low morbidity), increased visualization and instrument dexterity enabled by robotic technology provides further benefit compared to conventional thoracoscopy. Our data on a large number of patients are encouraging, particularly for early stage thymoma, despite a relatively short oncologic follow-up period. Extended resections for Masaoka stage III/IV may be possible for selected patients, but they are considered experimental.

Acknowledgements

None.

Footnote

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

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Robotic thymectomy—a new approach for thymus

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Abstract: Advancements in modern technology bring many evolutions in minimally invasive surgery such as robot assisted approaches. Because of complete resection is so important in thymectomy operations, they became a new era for robotic surgery as a result of its superiorities (intuitive movements, tremor filtration, more degrees of manipulative freedom, motion scaling, and high-definition stereoscopic vision).

Keywords: Robotic-assisted thoracic surgery (RATS); video-assisted thoracic surgery (VATS); thymectomy

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Introduction

The gold standard technique for thymectomy has been transsternal approach. The main advantages of this technique are asserted to have an optimal exposure and availability of the complete dissection of the thymus and mediastinal fatty tissue (1). By this way, the risk of possible incomplete thymectomy has been claimed to be zero, a complete healing from myasthenia gravis is possible (1). The risks of major vascular and phrenic nerve injuries are very low (1). Major disadvantages of this technique include that: splitting of the sternum, the longer duration of operation and postoperative hospitalization. For these reasons transsternal resections for nonthymomatous thymus have almost been tailed in major thoracic surgery centers.

One of the most commonly used approaches is the transcervical thymectomy. It is a minimally invasive technique which is mostly preferred by younger females and neurologists (2). The advantages of transcervical thymectomy are short hospitalization, and fewer complications (2). However, the main criticism includes the incomplete resection of thymus or perithymic fatty tissue due to crowding of instruments.

Video-assisted thoracic surgery (VATS) thymectomy gained popularity after 2000s. It can be performed via the left- or right-sided approach or even subxiphoidal or bilateral (3). The disadvantages of this technique are the 2-dimensional view of the operative field and the long learning curve (3).

Recently, robotic-assisted thoracic surgery (RATS) has become into as an alternative approach to either, open surgery or video-assisted thoracoscopic surgery. Resection of thymus in the treatment of myasthenia gravis and thymoma is also a new era for robotic-assisted surgery. A detailed radiologic examination is essential for selection of appropriate case for surgery also to decide the surgical approach. Patients with Myasthenia Gravis are examined by a qualified neurologist and anesthesiologist before surgery.

Our robotic (da Vinci Systems Intuitive Surgical, Sunnyvale, California) thymectomy technique with tricks is explained in detail in this presentation.

Preparation of surgery—positioning of the patient and docking of the robot

The right sided approach is preferred due to our long lasting experience with VATS. We give the patient a 30-degree semi-supine position. The patient is supported with a roll placed under the right shoulder, and the right arm

Figure 1 Under general anesthesia, patient right arm is draped and positioned inferiorly near the chest.

Figure 2 Incisions of right RATS thymectomy. RATS, robotic-assisted thoracic surgery.

Figure 3 The robot is docked to the patient.

Figure 4 Maryland bipolar forceps of da Vinci is used to dissect out the gland from the pericardium and sternum without disturbing the integrity of the capsule (4).
Available online: http://www.asvide.com/articles/1506

is draped and positioned inferiorly near the chest (*Figure 1*).

A double lumen endotracheal tube is placed with the help of a bronchoscope. Three ports are used in this surgery. The incisions are performed around the breast without violating the mammalian tissue (*Figure 2*). The first port is always the camera port and zero degree camera is used while placing the other ports. During the operation 30 degrees camera should be used when necessary. The left port is opened in the anterior axillary fossa and the right port is opened in the 5–6th intercostal space under the breast folds. We do not open an access port unless the operation is performed for a thymoma resection. On thymoma resections the left port is enlarged and an Alexis retractor (Applied Medical, Rancho Santa Margarita, CA, USA) is replaced. After the placement of the ports, side docking of the robot is performed (*Figure 3*).

Surgical technique

We use carbon dioxide insufflation with a pressure of 6 mmHg until we open contralateral mediastinal pleura. In the left arm a prograsper is used and for the right arm Maryland forceps is preferred. After the careful exploration of the cavity and the phrenic nerve, we begin the dissection with resection of the right sided pericardiophrenic fatty tissue. The resection of the thymus begins by dissecting the thymus on the pericardium anterior to the phrenic nerve with blunt dissection or Maryland forceps in the right hand (*Figure 4*).

Then the thymus is dissected from the sternum by

Figure 5 Respectively right upper pole then left upper pole are retracted by using a moderate amount of tension (5).
Available online: http://www.asvide.com/articles/1508

Figure 6 The major thymic vein is preparing (6).
Available online: http://www.asvide.com/articles/1509

opening the contralateral mediastinal pleura. The dissection on the superior vena cava parallel to the phrenic nerve enables visualization of the superior vena cava and junction of both innominate veins. The dissection of the upper poles needs caution. By gentle traction on the superior poles caudally, both superior poles of the thymus could be dissected separately from their attachments to thyrothymic ligament with their capsule without violating of the thymic tissue (*Figure 5*). The arterial and venous branches could be identified and divided during this maneuver. The major thymic veins may be at different numbers and locations and caution is needed to divide them carefully without causing hemorrhage (*Figure 6*).

After complete dissection of the upper poles, the thymus is retracted caudally, as follows it became completely freed from left innominate vein. The left side of the thymus could be dissected from the pericardium by pulling the thymic tissue toward the surgeon. By this way, the left phrenic nerve could be visualized. After completion of the left thymus resection, fatty tissue located at the left pericardiophrenic angle is completely resected.

The specimen is removed with an Endo bag (Covidien, USA) from the axillary port if an access port was not opened. The mediastinum is carefully inspected for any remaining fatty mediastinal tissue and hemostasis. One 10 mm Jackson Pratt drain is placed through the most anterior port across the mediastinum to drain the both chest.

Tips and tricks in resection of thymomas

If the operation is performed for a thymoma resection, the left port is selected as access port, because intercostal space is larger in this area and assistance could be performed from this port by an Alexis retractor. The thymoma should be resected at the last part of the operation and a non-touch technique should be performed during the whole surgery in robotic thymothymectomies, similar with VATS thymoma operations. For this reason, the non tumourous part of the thymus is dissected first and these tissues are used for grasping and traction.

Discussion

Despite the median sternotomy has been the gold standard for a long time (1,7), in the past 20 years, minimal invasive approaches have become accepted techniques for thymectomy (8).

In patients with thymoma the International Thymic Malignancy Interest Group (ITMIG) recommends a complete thymectomy for patients without myasthenia gravis (MG) and extended thymectomy for patients with MG. This kind of resections either prevent possible recurrences, or increase the possible remission rates (9). A neurological benefit and decreased use of steroids in the majority of patients after thymectomy has been reported (10). Incomplete thymectomy operations are unacceptable in patients with MG. This includes either the patient has a thymoma or not (11).

Robot technology is an evolution of manual videothoracoscopy introduced to overcome limitations of videothoracoscopic surgery such as rigid instruments and suboptimal vision (12). More intuitive movements, tremor filtration, more degrees of manipulative freedom, motion scaling, and high-definition stereoscopic vision are advantages of the robotic approach (13). As a consequence of these superiorities of robotic surgery, performing safer and complete thymus resections can be feasible.

Robotic thymectomy is a feasible and safe surgical technique with comparable perioperative outcomes to the open surgery in patients. A learning curve of 15–20 cases may be required by the surgeons to safely perform this relatively novel technique (14). Robotic thymectomy with good perioperative outcomes obtained, especially the team is experienced in videothoracoscopic surgery.

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Footnote

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Robotic thymectomy: technical tips

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Abstract: Thymectomy is the cornerstone in the treatment of thymic tumors and an accepted option for the multimodality management of myasthenia gravis (MG). Different surgical approaches have been described either open or minimally invasive. The introduction of robotic-assisted surgical systems has brought clear technical advantages over standard minimally invasive techniques. We present the surgical technique of robotic thymectomy that we apply for patients affected by myasthenia gravis and early stage thymoma.

Keywords: Thymectomy; thymoma; robot; myasthenia gravis

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Introduction

Thymectomy constitutes a widely accepted therapeutic option in the multidisciplinary management of MG and the cornerstone in the treatment of thymic tumors (1-3).

A variety of surgical approaches for thymectomy has been described, ranging from open to minimally invasive ones.

The introduction of robotic-assisted surgical systems has brought clear technical advantages over standard video-assisted thoracoscopy, particularly for surgical application in remote to reach or narrow anatomical regions, such as the mediastinum (4).

Patient selection and workup

Main indications for robotic thymectomy are patients with MG and patients with early stage thymic tumors associated or not with MG.

During pre-operative evaluation it is important to investigate if there are symptoms or clinical signs that could be related to MG and to evaluate the serum titer of antibodies against acetylcholine receptor. If negative, antibodies against the muscle specific receptor tyrosine kinase (anti-MuSK Ab) should be tested; there is evidence that thymectomy can be less effective in MG-patients with positive serum titer of anti-MuSK Ab (5).

There isn't a gold standard in surgery timing but it seems that in case of recent onset of symptoms there is higher possibility of remission or improvement after thymectomy (6). Age over 50 years or antibody-negative disease are relative contraindication to thymectomy in non thymomatous MG (7,8).

All patients should be evaluated with a contrast-enhanced CT scan of the chest. Magnetic resonance and/or PET-CT scan can also be performed. Extensive adhesions related to prior pleuritis or thoracic surgical procedure may preclude a robotic approach.

Functional assessment should be completed with pulmonary function tests, complete blood examination and electrocardiogram.

Pre-operative preparation

Neurological assessment prior to surgery should be always performed to evaluate presence of active or significant symptoms of MG or to optimize the medical treatment.

The patient is under general anesthesia intubated with a double-lumen endotracheal tube, for selective single-lung ventilation during the operation, and is monitored by electrocardiogram, arterial line, pulse oximeter and urine output.

Figure 1 Patient positioned on the operating bed, left side up at a 30-degree angle with a bean bag. Marked on the skin are the ports' access sites.

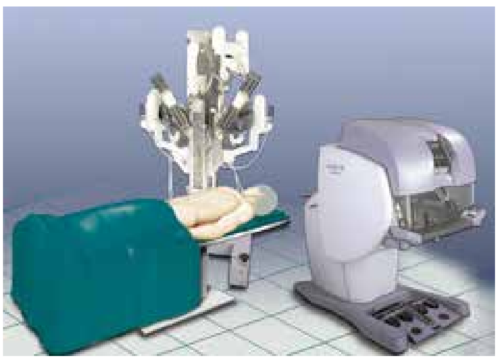

Figure 2 Schematic view of the robotic alignment in relation to the patient's position.

The patient is positioned left- or right-side up (depending from the side of operation) at a 30-degree angle with a bean bag. One arm is positioned along the body and the other is on a support parallel to the bed to better expose the axillary region on the side of operation (*Figure 1*). The robotic cart is positioned on the right side of the bed (left side for right-side approach) with a 45° angle (*Figure 2*).

The operative field should always be draped for an eventual open conversion.

Equipment preferences and cards

Different robotic systems have been developed in the past years but the most widespread is the Da Vinci robotic system (Intuitive Surgical, Inc., Sunnyvale, Calif).

It consists of a surgeon's computerized console, a vision system and a patient-side cart that supports the robotic arms (*Figure 3*). The surgeon controls the system sitting at the console far from the patient. The console represents the interface between surgeon and robotic system. The surgeon sees the operative field through a binocular localized in the upper part of the console and his fingers grasp the master controls below the display realizing the movements of robotic instruments. The system translates the movements of hands and fingers into precise, identical, and real-time movements of surgical instruments inside the patient. A support makes the movements comfortable and is furnished with several buttons for the regulation of various functions like the type of vision (2-D or 3-D view) the type of optic (0°–30°). Moreover, the system is equipped with a tremor filtering that allows for extremely precise movements. At the bottom of the console a series of 5 pedals permits other controls such as the activation of electrocautery, the variation of focal point of the camera, etc. (*Figure 4*).

The vision system contains the video components: a monitor that allows the operating-room personnel to view the intervention, and two boxes for control of the video-camera and for the balancing of luminosity and contrast of the image. A system for the supply of CO_2, and its intracavitary pressurization can be placed in this tower.

The patient-side cart supports the arms of the robot, the central one holding the 12-mm diameter optic. The left arm has an EndoWrist instrument that grasps the thymus; the right arm has an Endo-dissector device with electric cautery function (or a Harmonic ultrasound dissector) used to perform the dissection. The surgical instruments are articulated with the main arm and they are designed with seven degrees of motion and a 360° rotation, which mimics the dexterity of the human hands and wrist.

Procedure

A 12-mm camera port for the three-dimensional stereo endoscope is introduced through an incision on the fifth intercostal space on the anterior/midaxillary line and two additional 8 mm thoracic ports are inserted; one on the third intercostal space on the midaxillary region and another on the fifth intercostal space on the parasternal space. After placing the first port, it is advantageous to use the camera to help placing the other two ports so that their trajectory line is correct and to avoid lesion of the heart or pericardium when placing the parasternal port. Two arms

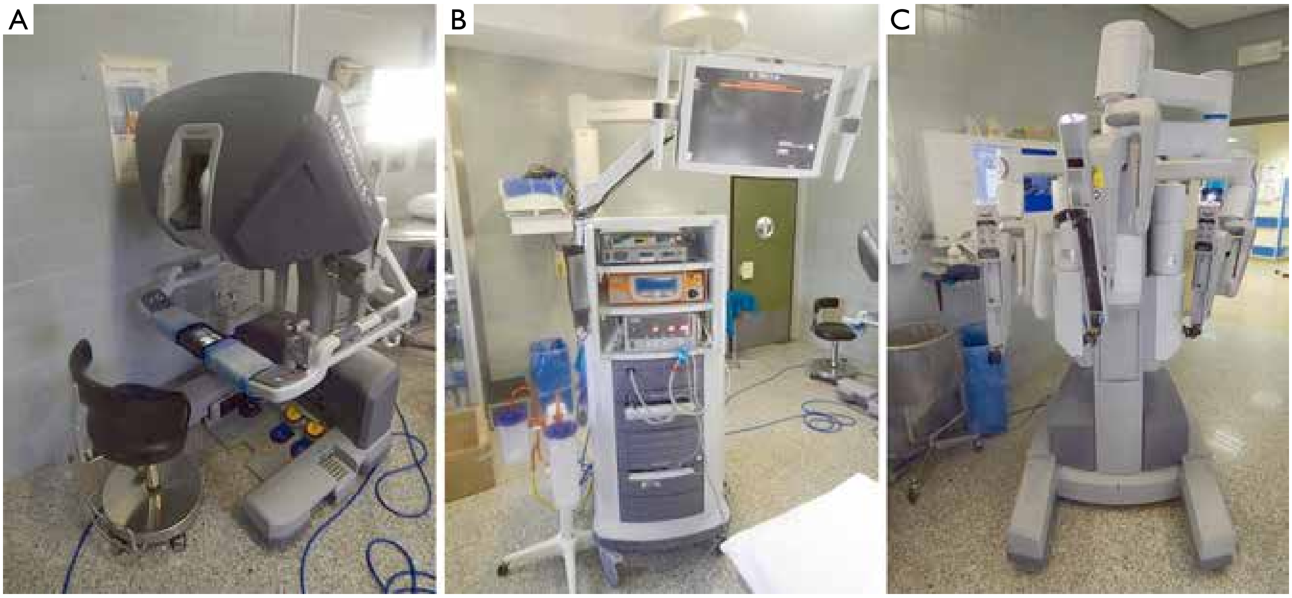

Figure 3 Robotic components. (A) Surgeon's console; (B) vision system; (C) patient-side cart with robotic arms.

Figure 4 Close look to the surgeon's console: binocular (*), master controls (arrows), buttons and pedals.

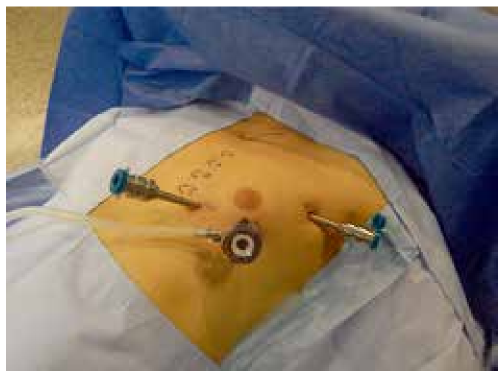

Figure 5 Ports positioned: two ports for the robotic arms laterally and camera-port with CO_2-connecting line in the middle.

of the da Vinci system are then attached to the two access points and another arm is attached to the port-inserted endoscope (*Figure 5*).

The hemithorax is inflated through the camera port with CO_2 (pressure ranging between 6 and 10 mmHg) to obtain a clear view within the chest and to allow an easier dissection as it extends the mediastinal space.

First, a careful exploration of the mediastinal left pleural space is performed to exclude the presence of any pleural implants in case of thymic tumors. Then, the field of the surgical dissection is individuated in a triangle area with the basis at the bottom of pericardium where the fat tissue of the left and right pericardiophrenic angles is localized. The lateral borders of the triangle are delimited by the mammary vessels anteriorly and by the left phrenic nerve posteriorly, with the apex located in the neck (*Figure 6*).

When a left-sided approach is performed, the dissection starts inferiorly at the left pericardiophrenic angle and continues along the anterior border of the phrenic nerve.

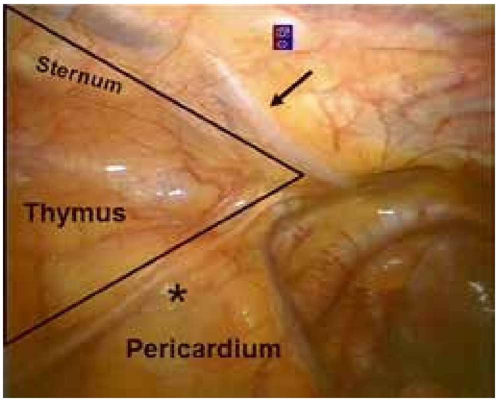

Figure 6 Surgical field individuated in a triangle area within the left phrenic nerve (*) and the mammary vessels (arrow).

All anterior mediastinal tissue, including fat, is isolated from the phrenic nerve. Caution must be paid not to damage the nerve, therefore during dissection it may be useful if the table-site assistant puts a hand on the patient abdomen to perceive any hemidiaphragm contraction. The left inferior horn of the thymus is then located and dissected from the pericardium. Subsequently, the thymic gland is separated from the retrosternal area until the right mediastinal pleura and the right inferior horn are found (*Figure 7A-C*). The lower part of the thymus is then mobilized upwards until the level of aortic arch. At the top of the mediastinum, the pleura is incised in the area delimited by the mammary vessels in the anterior limit and by the phrenic nerve in the posterior limit (*Figure 7D*). The dissection continues upward to the neck until the superior horns are identified and divided from the inferior portion of the thyroid gland by a blunt dissection (*Figure 8A*). Grasping and pulling the superior horns below, the innominate vein is then identified and dissected along its border up to the point where the

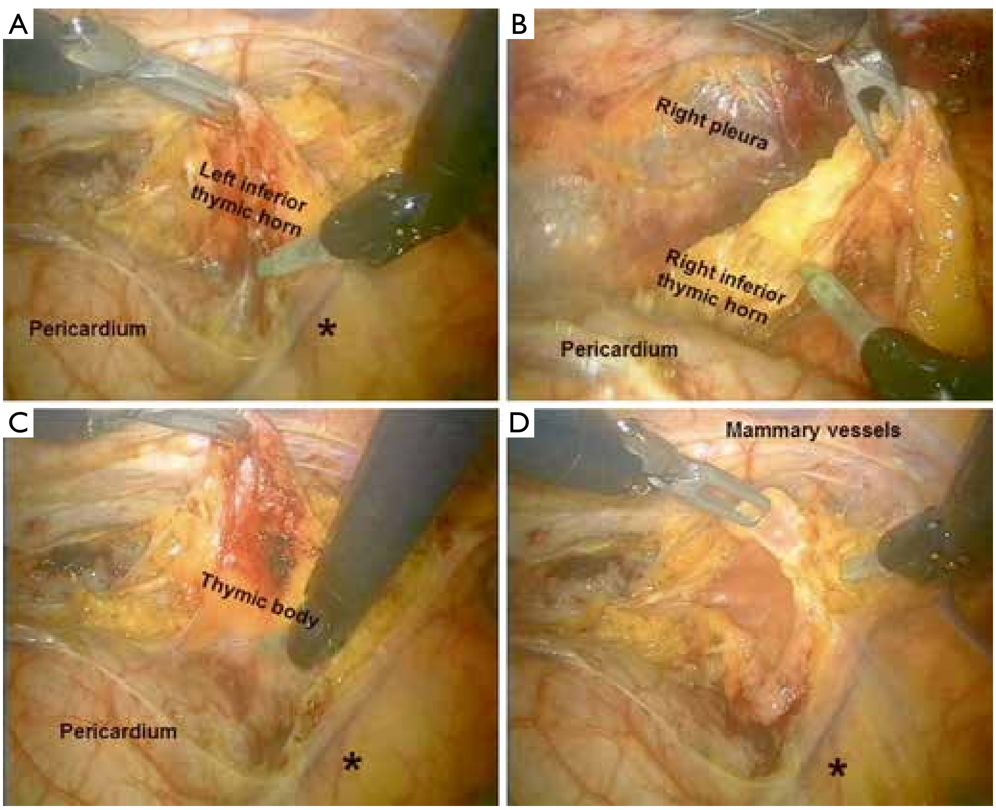

Figure 7 Surgical technique. (A) Dissection of the left inferior horn of the thymus; (B) dissection of the right inferior horn, detecting the right pleura; (C) dissection of the thymus from the pericardium; (D) the dissection moves upwards to the neck between the mammary vessels and the phrenic nerve (*).

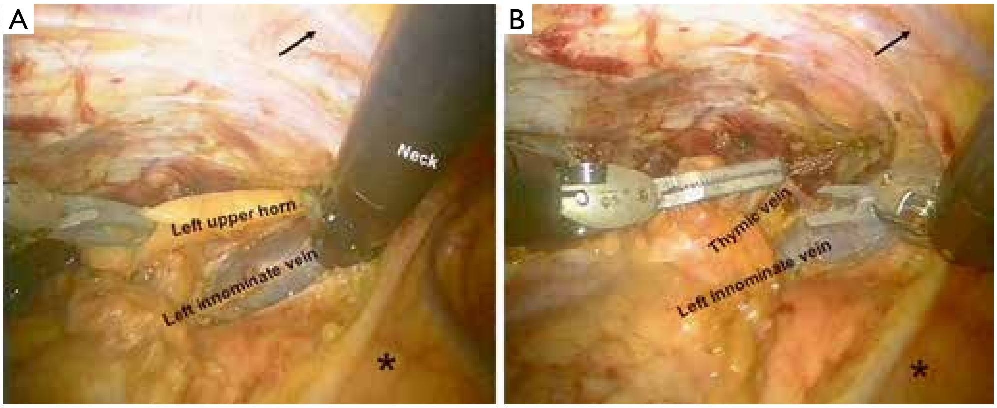

Figure 8 Surgical technique. (A) Dissection of the left upper horn of the thymus above the left innominate vein; (B) dissection and clipping of a thymic vein (*, phrenic nerve, arrow, mammary vessels).

Figure 9 Team members during operation.

thymic veins are identified, clipped and divided (*Figure 8B*).

The thymus gland, the anterior mediastinal, and the neck fatty tissues are radically resected and the specimen is placed in an Endobag and removed through trocar incision.

In the right side approach, dissection begins from the cardiophrenic angle and the mediastinal pleura is incised just anterior and medial to the right phrenic nerve, then continues upwards till all anterior mediastinal tissue is separated from the nerve. At this point starts the dissection onto the sternum and the division of the pleura along the right internal mammary artery and veins from the origin all the way to the diaphragm. The next step involves elevating the thymus off the pericardium, starting from the inferior horns and heading upwards until the left brachiocephalic vein is encountered. The thymus is dissected off the anterior aspect of the vein and the thymic veins are identified, clipped and dissected. Then the superior horns are identified and divided from the thyroid gland. The left pleura is then opened and after the left phrenic nerve is identified, the dissection of the thymus is completed.

After the hemostasis, a 28F drainage tube is inserted through the port of the fifth intercostal space, the lung is inflated, and the other wounds are closed.

Role of team members

Surgical team should be composed by 2 surgeons, 1 anesthetist, 1 scrub nurse and 1 operating room nurse. One surgeon is at the robotic console, controlling the robot. The other is table-site surgeon that must perform the incisions and introduce the ports. Moreover, he must be able to perform the connection between the robot and the ports and to rapidly undock the system and perform an emergency sternotomy in case of uncontrollable vascular bleeding or any other complication. The scrub nurse must be trained in the use of robotic material and able to exchange the robotic instruments. The anesthesiologist should be experienced in the management of patients undergoing thoracic procedures and of patient with MG (*Figure 9*).

Post-operative management

The patient is generally extubated in the operating room and, after an adequate period of observation, returns to the ward. In some cases (i.e., patients with MG not well controlled pre-operatively) the patient may be transferred to the ICU for monitoring.

The chest drain is removed if the postoperative chest X-ray shows normal findings and the amount of pleural fluid is permissive, generally 24 hours after operation. If neurological evaluation is satisfactory, the patient is discharged 48–72 hours after surgery.

Tips, tricks and pitfalls

Different issues regarding robotic thymectomy are still matter of debate.

First is the better side to perform thymectomy. Authors supporting the left-sided approach point out that the left lobe of the thymus gland is usually larger and extends down to the pericardiophrenic area, and that the aortopulmonary window and the region below the left innominate vein are frequent sites of ectopic thymic tissue. The thymus may also extend lateral to or under the left phrenic nerve, or descend totally or partially posterior to the innominate vein (9). Moreover, the right phrenic nerve is protected by the superior vena cava in the high mediastinum and may be identified and easily followed in the lower part (10,11).

Authors who prefer a right-sided approach emphasize the larger operative field, the better visualization of the venous confluence by following the superior vena cava, the easier visualization of the aortocaval groove and a better ergonomic position to accomplish dissection making it easier in the early part of the learning curve (9,12,13).

Anyway, the approach should be tailored on the patient's anatomy in order to perform a complete dissection of all the thymic tissue and the mediastinal fat which may contain foci of ectopic thymus in patients with MG (14). A particular care should be used when left innominate vein is dissected in order to avoid a major bleeding: when a small thymic vein is encountered and clipped, it is mandatory to search for a second vein that usually is present at the level of left innominate/superior vena cava angle. In about 5% to 10% of cases an anatomical variation is present: the most common is the upper left horn running behind the innominate vein and over the subclavian or carotid artery. In case of right sided approach, the dissection of the abnormally positioned left upper horn may be very difficult.

Correct selection of patients is mandatory in case of thymomas, in order to avoid complications and achieve the best result from the oncological point of view.

Cheng *et al.* proposed some radiological criteria for candidates to minimally invasive thymoma resection: the location in the anterior mediastinum, the tumor encapsulation, a distinct fat plane between the tumor and vital organs, the existence of residual normal appearing thymic tissue, no mass compression effect and unilateral tumor predominance, particularly for tumors of dimension greater than 3 cm (15).

A large tumor size (3–5 cm) may not be an absolute contraindication, however, it could make manipulation more difficult, with increased chance of open conversion or prolonged operative time (11).

Thymomas should be resected using a "no-touch" technique, removing the tumor en-bloc with the surrounding thymus and fatty tissue and care should be taken to avoid rupture of the capsule with increased risk of pleural dissemination (16). This technique requires a more complex and accurate dissection, thus a longer learning curve and operative time (11).

If an initial attempt of minimally invasive approach is deemed by the surgeon to be unlikely to be completed, both for the risks of the procedure itself or possible violation of any principle of oncologic safety, open conversion is mandatory.

Major disadvantages have been described regarding robotic surgery. Some authors pointed out the lack of tactile feedback that could theoretically increase the risk of damaging delicate structures. Anyway, this disadvantage seems to be widely compensated by the superior view of the operating field through the 3-dimensional vision (11,17). Another disadvantage concerns the placement of the surgeon, away from the patient and operating at a non-sterile console (17). Thus, another surgeon able to perform an emergency conversion needs to stay sterile near the robot.

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Footnote

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

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Technique of robotic assisted minimally invasive esophagectomy (RAMIE)

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Abstract: Minimally invasive esophagectomy (MIE) has gained popularity over the last two decades as an oncologically sound alternative to open esophagectomy. Robotic assisted minimally invasive esophagectomy (RAMIE) has been developed at few highly-specialized centers, and overall experience with this technique remains limited. Herein, we describe our overall approach to this operation and specific technical issues.

Keywords: Esophagectomy; robotic; minimally invasive; esophageal cancer

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Introduction

Esophagectomy remains a central component in the therapy of esophageal cancer and the salvage therapy of choice in many benign esophageal pathologies. Despite having been described more than a hundred years ago, esophagectomy remains an operation with potential high morbidity and mortality outside of specialized centers (1-3). To maximize the benefit of the procedure while minimizing its risks, surgeons have sought to refine the procedure. Minimally invasive approaches to esophagectomy were first described in the 1990's, and recent works have demonstrated oncologic equivalence and safety in total laparoscopic/thoracoscopic trans-thoracic minimally invasive esophagectomy (MIE) compared to open operations (4,5).

The first reports of robotic assisted minimally invasive esophagectomy (RAMIE) were published in the early 2000's (6,7). Though overall utilization of robotics in esophagectomy is low, a relative boom in the increase of the use of RAMIE has been seen in recent years. Various specialized centers such as the University of Alabama, Memorial Sloan Kettering, and our own institution (University of Pittsburgh) have since described their individual initial experiences and approaches to total laparoscopic/thoracoscopic RAMIE, demonstrating the relative safety of the procedure (8-10). Some centers, including our own, have suggested the robotic platform offers several potential advantages that significantly facilitate and improve the primary surgeon's control over the conduct of the operation, related primarily to superior instrument dexterity, stable high definition and stereoscopic visual capabilities, and multi-arm platforms allowing surgeon self-assist. Herein, we describe our Ivor Lewis approach to RAMIE, which represents the majority of operations we perform for lower esophageal tumors. The current report describes our approach with the most current available robotic platform (DaVinci Xi, Intuitive Surgical Inc., USA).

Patient selection

Patients considered for esophagectomy are preoperatively evaluated for significant comorbidities, cardiopulmonary fitness, and functional status. All patients preoperatively obtain a formal pathologic diagnosis with esophagogastroduodenoscopy and biopsy, endoscopic ultrasound, fluorodeoxyglucose-18

Figure 1 This video demonstrates the key steps in performing a successful robotic assisted minimally invasive esophagectomy (11). Available online: http://www.asvide.com/articles/1677

positron emission tomography, and computed tomography of the chest abdomen and pelvis. Bronchoscopy is routinely performed for middle and upper esophageal tumors to assess airway involvement. Many patients undergo a laparoscopic staging procedure for evaluation of metastatic disease, surgical resectability, and placement of a chemotherapy infusion port when induction treatment is warranted. Patients with T3 disease or N1 disease are referred for neoadjuvant chemotherapy and/or radiation therapy. Patients considered suitable for an MIE approach are also considered appropriate for RAMIE.

Equipment preference card

- Robotic platform: DaVinci Xi Robotic Surgical System with 30-degree camera system and near infrared imaging (Firefly, Intuitive Surgical, USA).
- Robotic 8 mm instrumentation: fenestrated bipolar grasper, robotic ultrasonic shears, small grasping retractor, large needle driver, large suture cut needle driver, Cadiere forceps, Maryland bipolar forceps (as indicated), shears.
- The 28 mm extended/long EEA circular stapler (DST XL, Covidien, USA).
- Anastomotic purse string suture: 2-0 and 0 polypropylene on SH needle (Prolene, Ethicon, USA).
- Other suture: 2-0 on SH needle (Ethibond, Covidien, USA).
- Other: 5 mm suction/irrigator system, 5 mm 30-degree standard laparoscope, 12 French percutaneous jejunostomy and introducer, Endostitch device with 2-0 surgical suture (Covidien, USA), 10 mm medium/large clip applier (Covidien, USA).

Operative technique (*Figure 1*)

Abdominal approach

The patient is placed in the supine position and shifted to the right side of the bed to facilitate use of the liver retractor (DiamondFlex, Snowden Pencer, USA) and stabilization system (MediFlex, USA). Esophagogastroscopy is performed in every case by the operating surgeons to assess suitability of the stomach for later gastric conduit creation. The left arm is tucked to the patient's side and the right arm left abducted. A footboard is placed for support during reverse Trendelenburg positioning.

Port placement

A midline robotic 8mm is placed using an open cut down technique at the level of the umbilicus. Standard CO_2 insufflation is utilized at a pressure of 15 mmHg. The 8 mm ports are then placed in mid right and left mid clavicular line and at the left costal margins. A standard 5 mm port is as posterior as possible at the right costal margin while avoiding the right colon and a liver retractor is placed through it. A robotic atraumatic grasper (small grasping retractor) is placed in the left most costal port, an ultrasonic shear in the left midclavicular port and a bipolar forcep in the right midclavicular port. A 12 mm robotic stapler port is placed in the right para umbilical position for use as a bedside assist and for later stapler use. Alternatively, if standard staplers are to be used, a routine 12 mm port may be placed. An additional 5 mm port is placed further lateral in the same para umbilical line for use by the assistant's left hand.

Hiatal dissection and retrogastric dissection

The dissection begins with the division of the lesser omentum and assessment of the resectability of the tumor including the celiac axis, crura, aorta, and pancreas. All lymphatic tissues from the proximal common hepatic, splenic, and left gastric arteries, as well as retrogastric basins are dissected and swept above the line of division of the left gastric artery for later *en bloc* removal with the surgical specimen. This dissection is facilitated by anterior retraction of the stomach with the left most small grasping retractor. A vascular stapler is used to divide the left gastric. In the event of a significant replaced left hepatic artery arising from the left gastric artery, the common origin and left gastric artery are carefully skeletonized of all lymph node bearing tissues and divided distal to the origin of the replaced hepatic artery, preserving the replaced hepatic artery in its entirety. Through this retrogastric exposure, significant retrogastric adhesiolysis and mobilization of the gastric fundus can be achieved from the pancreas to the left crus and along the spleen, including initial division of the short gastric arteries.

Gastric mobilization and conduit creation

Gentle medial and superior retraction of the stomach with the robotic retractor arm while using a "no touch technique" on the greater curve aids the division of the short gastric vessels from the mid body of the stomach to the left crus. The gastroepiploic arcade is fully preserved along the greater curvature. If available, near infrared imaging with indocyanine green (Firefly, Intuitive Surgical, USA) can be used to identify the entire course of gastroepiploic artery, which may be useful patients with significant intra-abdominal adiposity. In patients who have received induction chemoradiation therapy, a pedicled omental flap based off 2 omental perforating arteries is created as a buttress for later reinforcement of the intrathoracic anastomosis. Development of this flap is aided by medial retraction of the stomach and lateral retraction of the omentum. The stomach is fully mobilized from the crura to the pylorus, ensuring especially that all retrogastric and retropyloric adhesions are lysed. This maneuver is made easier by superior and medial retraction using the small grasping retractor from either under the stomach, or with gentle grasping of the stomach antrum below the intended point of conduit creation.

Pyloroplasty

The pylorus is retracted superiorly and leftwards for exposure with a gentle grasp on the distal gastric antrum by the small grasping retractor. Braided, non-absorbable hemostatic sutures are placed at the superior and inferior aspect of the pylorus and aid in retraction (2-0 Ethibond, Covidien, USA). The pyloroplasty is routinely performed in a Heinecke-Mikulicz fashion with the initial incision through the pylorus performed with the ultrasonic shears. The pyloroplasty is completed with approximately 5–6 robotically placed interrupted sutures.

Conduit formation

The robotic small grasping retractor retracts the fundic tip to the left upper quadrant against the diaphragm. Sequential applications of the straight 45mm robotic gastrointestinal stapler are used to create a straight, narrow gastric conduit approximately 4–5 cm in width. The gastric conduit is secured to specimen in proper orientation for later traverse into the chest and the omental flap is tacked to the tip of the gastric conduit to facilitate locating it and manipulating it during the thoracic portion of the operation. Lastly a marking stitch is placed at the transition of gastric conduit to antral reservoir. Feeding jejunostomy is performed using standard laparoscopic equipment and techniques to facilitate the surgeon's transition back to the bedside in preparation for lateral positioning. The abdomen is inspected for hemostasis and the abdominal portion of the operation is concluded.

Thoracic approach

Patient positioning and port placement

The patient is placed in standard left lateral decubitus position. A Veress needle is inserted just below the tip of the scapula to allow for CO_2 insufflation. The intrathoracic pressure is set to 8 mmHg. The robotic 8 mm ports are sequentially inserted at the eighth intercostal space at the posterior axillary line, the third intercostal space in the mid to posterior axillary line, fifth intercostal place into the mid axillary line, and at the ninth intercostal space approximately in line with the tip of the scapula under direct vision. A 12 mm robotic stapler/assistant port is placed just above the diaphragmatic reflection. The robotic cart is driven over the patient's right shoulder. The camera is placed into the eighth intercostal space port, a bipolar retractor in the ninth intercostal space port, a harmonic scalpel in the 5th intercostal space and small grasping retractor in the third intercostal space port.

Esophageal mobilization

The pleura over the esophagus anteriorly and posteriorly are opened using the ultrasonic shears. The esophagus is mobilized circumferentially from the hiatus to the level of the azygos vein, ensuring all node bearing tissues are harvested with the esophagus. When harvesting the subcarinal lymph nodes, energy must be meticulously and sparingly applied when working near the airway, in particular the posterior membranous structures of the trachea, mainstem bronchi, and bronchus intermedius. Clear visualization, meticulous use of energy, sharp dissection and blunt dissection are critical to thermal injuries which may significantly increase the risk of entero-bronchial fistulae. This caution cannot be overemphasized. While this can often be achieved with use of the ultrasonic shears, alternative use of the Maryland bipolar forceps may be advisable during this portion of the dissection if the ultrasonic shears cannot be utilized in a relatively parallel orientation the bronchus intermedius and right mainstem bronchus. Early identification of the trachea may facilitate early and clear identification of the left mainstem bronchus, which tends to be "deeper" and more obscured in the surgical field. Along the posterior pleura, clips are used liberally to ligate large lymphatic and arterial perforating vessels from the thoracic duct and aorta respectively. Hiatal dissection is completed and the surgical specimen and proximal conduit brought into the chest with careful attention to maintain proper orientation of the conduit. The proximal conduit is separated from the specimen, partly delivered into the chest, and temporarily sutured to the diaphragm. The "deep" medial dissection is completed along the contralateral pleura and greatly facilitated by lateral retraction of the specimen by the small grasping retractor. Care must be taken to avoid injury to the left mainstem during this dissection if not fully visualized at the time of the subcarinal dissection. The esophagus is mobilized towards the thoracic inlet with division of the vagus nerves at the level of the azygos vein to prevent traction injuries to the recurrent laryngeal nerve. The azygos vein is divided with the robotic vascular stapler. Firm retraction is utilized to maximize visualization. The esophagus is sharply divided approximately three centimeters above the azygos vein using the robotic shears. The surgical specimen is removed through the fifth intercostal surgical port, which is extended to a 4 cm mini access incision along with placement of a wound protector device. This incision will later serve as the entry point for the anastomotic stapler.

Esophagogastric anastomosis

A running "baseball" purse string suture is placed at the esophageal orifice with 0 polypropylene suture on an SH needle (Prolene, Ethicon, USA). The robotic graspers hold the orifice of the proximal esophagus. and the 28 mm anvil of the extra-long end-to-end anastomotic (EEA) stapler is inserted (DST XL, Covidien, USA). An additional purse string suture is placed to reinforce this staple purse string suture. The EEA stapler is introduced through the access incision and is placed through a gastrostomy in the proximal conduit. The stapler spike is advanced out through the lateral wall of the conduit just above the level of the vascular arcade insertion. The stapler and anvil are docked ensuring flush apposition of the tissues and appropriate orientation. The stapler is fired and the anastomosis completed. Redundant conduit is resected with the robotic gastrointestinal stapler. If an omental flap has been previously harvested, it is secured around the anastomosis. It is advisable to maintain a modest amount of fat along the lesser curve to provide tissue between the airway and gastric conduit and anastomosis. A nasogastric tube is placed and its position in the conduit confirmed under direct vision. A small drain is placed posterior to the anastomosis and a chest tube is left in the right pleural space.

Postoperative care

Postoperatively, routine patients are admitted to the ICU and discharged the next day to the step-down ward. Enteral nutrition is initiated via jejunostomy tube on postoperative day 2. A barium swallow is performed after removal of the nasogastric tube on postoperative day 4–5 and a liquid diet initiated. All patients are discharged with their peri-anastomotic drain, which is removed at the first outpatient clinic follow up visit.

Tips, tricks and pitfalls

- ❖ If possible, a dedicated robotic team should perform these cases. The majority of delays, technical glitches and errors are avoidable and are easily dealt with by an experienced team.
- ❖ Small capillary networks that support the area of the conduit used for the anastomosis can easily be damaged by the robotic graspers. To avoid any compromise of the conduit microvasculature, a "no-touch" technique must be adhered to at all times when mobilizing the greater curve of the stomach. Direct grasping and instrumentation of the greater curve of the stomach must be avoided at all times. Virtually all exposures can be readily achieved with standardized robotic retraction techniques.
- ❖ Maintain orientation of the conduit when attaching it to the specimen during the abdominal phase. Rotation of the conduit, or uncertainty regarding its orientation, may necessitate re-exploration in the abdomen, and is easily avoidable. This can be prevented by attaching the conduit using either two separate stitches or a wide horizontal mattress suture to prevent twisting or spiraling of the conduit
- ❖ Thermal injury to the posterior airway during the mediastinal dissection must be avoided. Operative assistants can provide additional exposure and aggressive suction as needed to maintain optimal visualization, and ultrasonic shears can be exchanged for lower-energy Maryland bipolar forceps to reduce the amount of radially-displaced energy.

Discussion

Our approach to Ivor Lewis RAMIE is described in detail. Due limited utilization currently, extensive data on the advantages of RAMIE as compared to MIE or traditional open esophagectomy is limited. Our initial experience with RAMIE at the University of Pittsburgh has been reported with favorable outcomes, with no 30- or 90-day mortality (8). Perioperative outcomes, including blood loss, anastomotic leak rates, and morbidity are similar to reported MIE outcomes at UPMC. The quality of the initial institutional experience has been greatly aided by the extensive previous experience and expertise of the two senior authors of this publication (IS Sarkaria and JD Luketich). The previously published experience by one of the senior authors (IS Sarkaria) at Memorial Sloan Kettering Cancer Center reported excellent outcomes in 100 patients undergoing RAMIE with an anastomotic leak rate of 6%, 0% 30-day mortality, and a 90-day mortality rate of 1% (12).

The robotic platform offers many potential advantages to this specific operation. Dissection of the hiatus and mediastinum can be very challenging with traditional laparoscopic and thoracoscopic instruments, especially in obese patients and those with robust responses to induction radiation therapy. Superior visualization and optics, as well as the extra degrees of freedom provided by the robotic instrumentation, may facilitate ease and conduct of dissection. With the conduct of the operation predominantly under the operating surgeon's control, the surgeon is less reliant on the input and coordination of operative assistants, which can help streamline the overall conduct of the operation. Specific portion of the MIE, such as pyloroplasty and anvil placement during creation of the anastomosis, is greatly aided by robotic suturing, which often provides improved precision and visualization. Although these potential benefits are compelling to surgeons using these platforms, measurable clinical benefit to the patient over standard MIE may or may not be demonstrable, for example, within the auspices of a clinical trial. Also, the financial implications associated with RAMIE are yet unknown and warrant further study.

It is of utmost importance to maintain a strong focus on patient safety and outcomes when developing a RAMIE program. Preparation with simulation, team building, observation of cases, cadaveric laboratory time, and appropriate expert mentorship and proctoring may be greatly beneficial in avoiding the known pitfalls and morbidity of these operations. With appropriate preparation and graded accumulation of experience, recapitulation of mortal technical complications, such as airway fistulae, should be near-completely avoidable in these complex operations. Within the scope of these cautions, the potential technical advantages of RAMIE may certainly be realized by surgeons wanting to adopt this technique.

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Footnote

Conflicts of Interest: IS Sarkaria is a Speaker for Intuitive Surgical.

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Robotic technological aids in esophageal surgery

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Abstract: Robotic technology is an emerging technology that has been developed in order to overcome some limitations of the standard laparoscopic approach, offering a stereoscopic three-dimensional visualization of the surgical field, increased maneuverability of the surgical tools with consequent increased movement accuracy and precision and improved ergonomics. It has been used for the surgical treatment of most benign esophageal disorders. More recently, it has been proposed also for patients with operable esophageal cancer. The current evidence shows that there are no real benefits of the robotic technology over conventional laparoscopy in patients undergoing a fundoplication for gastroesophageal reflux disease (GERD), hiatal closure for giant hiatal hernia, or Heller myotomy for achalasia. A few small studies suggest potential advantages in patients undergoing redo surgery for failed fundoplication or Heller myotomy, but large comparative studies are needed to better clarify the role of the robotic technology in these patients. Robot-assisted esophagectomy seems to be safe and effective in selected patients; however, there are no data showing superiority of this approach over both conventional laparoscopic and open surgery. The short-term and long-term oncologic results of ongoing randomized controlled trials (RCTs) are awaited to validate this approach for the treatment of esophageal cancer.

Keywords: Robotic; fundoplication; myotomy; esophagectomy

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Introduction

During the last 25 years, there has been a shift in the surgical approach to most esophageal diseases. Nowadays, the minimally invasive approach is standard of care for the surgical management of gastroesophageal reflux disease (GERD), achalasia and symptomatic epiphrenic diverticula. Patients treated laparoscopically have significantly better postoperative short-term outcomes than patients treated with an open approach, with similar long-term functional outcomes. More recently, the implementation of minimally invasive approaches occurred also in patients with esophageal cancer, leading to lower cardiopulmonary complications rates and shorter hospital stay.

However, conventional laparoscopic surgery has some drawbacks, including the 2-dimensional vision of the surgical field, tremor and limited degrees of freedom of the surgical tools movements. Robotic technology has been developed aiming to overcome these limitations of the standard laparoscopy. It offers several potential technical improvements, such as the three-dimensional visualization of the operating field, increased movement accuracy and precision secondary to the enhanced maneuverability of the surgical tools, and better surgeon ergonomics. To date, several studies have been conducted aiming to assess the benefits and the limitations of this technology for esophageal diseases (1-4).

The aim of this article is to critically revise the evidence available about the use of the robotic technology for the treatment of both benign and malignant esophageal diseases.

Robotic fundoplication for GERD

A laparoscopic total fundoplication is the surgical procedure of choice for the treatment of GERD. Patients experience very low perioperative morbidity and recovery is very fast. Good to excellent control of GERD-related symptoms is obtained in the vast majority of patients at 10 years after surgery.

During the last 15 years, the robotic technology has been proposed to further enhance the surgical results, mainly through a 3-dimensional vision and increased dexterity during the creation of the wrap. Several studies [five prospective randomized controlled trials (RCTs)] have compared robotic and conventional laparoscopic total fundoplication for GERD (5-9). For instance, we randomized 50 GERD patients to robot-assisted fundoplication (n=25) or to standard laparoscopic fundoplication (n=25) (6). The da Vinci Surgical System was used to perform all robotic surgeries. Robotic fundoplications took significantly longer than standard laparoscopic fundoplications (mean total operative time 131.3 *vs*. 91.1 min, P<0.001). None of the 50 procedures were converted to open surgery, while one of 25 robot-assisted fundoplications was converted to standard laparoscopic fundoplication. No significant differences were observed in the length of hospital stay. Higher total costs were recorded in the group of patients undergoing robotic surgery (euro 3,157 *vs*. euro 1,527; P<0.001). There was no surgery-related mortality. With a mean follow-up of 22.3 (range, 6–32) months, no significant differences in symptom control, endoscopic findings and functional outcomes were observed between the two groups. At 1 month after surgery, mild transient dysphagia rate was 12% (n=3) in each group. The GORD-HRQOL score analysis failed to show any significant difference in symptoms and quality of life at 3, 6 and 12 months postoperatively. At 6 months after surgery, upper endoscopy did not show esophagitis in any of the 50 patients; however, Barrett's esophagus did not regress in those patients who were diagnosed with preoperatively.

A recent meta-analysis (2) of the 5 RCTs including a total of 160 patients showed that the robotic and the standard laparoscopic approach are similar in conversion to laparotomy, length of hospital stay, dysphagia at 1 month after surgery, and need for redo surgery. These findings from small RCTs have been confirmed by the analysis of the large University Health System Consortium (UHC) database, including a total of 9,572 laparoscopic and 339 robot assisted fundoplication performed between 2008 and 2012 in the United States (10).

Only a few studies have assessed the esophageal function and the reflux profile by esophageal manometry and 24-hour pH monitoring. Frazzoni *et al*. (11) found in a retrospective review of 88 patients treated by standard laparoscopic (n=44) or robotic (n=44) Nissen fundoplication no postoperative differences in lower esophageal sphincter (LES) pressure between the two groups, while the esophageal acid exposure was significantly lower after robotic surgery. Abnormal values were observed in 6 (14%) and in none of patients after standard laparoscopic and robotic Nissen fundoplication (P=0.026). The authors concluded that the robotic fundoplication should be the approach of choice in those Institutions where the robotic technology is available. They suggested that the better results obtained after robotic surgery were the consequence of movement filtrations, enhanced view, and very limited bleeding. Unfortunately, two RCTs (6,7) did not confirm these findings. We found (6) that the resting pressures of the LES were similar after robotic or standard laparoscopic fundoplication: patients undergoing robot-assisted fundoplication had a mean resting LES pressure of 21.8 mmHg, while patients undergoing conventional minimally invasive fundoplication had a mean LES resting pressure of 22.3 mmHg (P=0.503). Postoperative 24-hour ambulatory pH monitoring showed normal values in all patients, with no differences between robotic and standard laparoscopic surgery groups in the mean DeMeester score (5.8 and 4.2, P=0.231). Similar perioperative outcomes and functional results were observed by Draaisma *et al*. (7) in a RCT comparing 25 patients undergoing laparoscopic Nissen fundoplication and 25 patients submitted to robot-assisted Nissen fundoplication for GERD.

In conclusion, the current evidence shows the equivalence in conversion and complication rates between laparoscopic and robotic approach. In-hospital outcomes, quality of life and functional outcomes are also similar, while the use of robotic technology is associated with longer operative time and higher total costs. Based on the lack of additional benefits, the use of the robotic technology for the surgical treatment of GERD is not considered justified and therefore it has been abandoned in many centers.

Robotic giant hiatal hernia repair

The laparoscopic approach for the surgical treatment of giant hiatal hernia is effective with limited morbidity and negligible mortality. However, it is technically demanding that requires advanced skills in upper GI laparoscopic surgery and recurrence rates are high. Robotic technology with the stereoscopic vision might help the surgeon perform a more precise dissection of the sac and the esophagus, reduction of the herniated organs into the abdomen, and cruroplasty (12). To date, very few studies have specifically assessed the impact of the robotic technologies on the outcomes in patients undergoing minimally invasive repair of a giant hiatal hernia, showing no real clear benefits to the patients. No long-term follow-up are available. Gehrig *et al.* (13) conducted a case-control study comparing 12 patients operated with the aid of the robot and 17 patients undergoing laparoscopic hiatal hernia repair. No advantages were found in operative time, intraoperative complications and early postoperative course.

Robotic Heller myotomy for achalasia

Laparoscopic Heller myotomy with partial fundoplication is currently the standard of care for the treatment of achalasia. It is associated with symptom improvement or relief in about 90% of patients. However, it is a challenging procedure with the potential risk of esophageal perforation reported in up to 10% of cases. Recently, the use of the robotic technology has been proposed claiming that it might reduce intraoperative esophageal perforation rates and improve postoperative quality-of-life after Heller myotomy, mainly due to the 3-D view and enhanced dexterity of the surgeon (3). However, comparative data are scarce (14-16). For instance, Huffmanm *et al.* (15) prospectively evaluated 61 consecutive achalasia patients submitted to standard laparoscopic or robot-assisted myotomy. A total of 37 patients were treated with a standard laparoscopic Heller myotomy, while 24 patients underwent robotic Heller myotomy. Operative time was longer in the robotic group (355 *vs.* 287 minutes). Intraoperative estimated blood loss was similar. No esophageal perforations or other operative complications were recorded during robotic surgeries, while 3 esophageal perforations (8%) occurred during standard laparoscopic Heller myotomy. Patients after robotic surgery had significantly better SF-36 Role Functioning (emotional) and General Health Perceptions than patients interviewed after standard laparoscopic surgery. Horgan *et al.* (16) retrospectively evaluated a total of 121 patients undergoing Heller myotomy: 59 patients had a robotic Heller myotomy and 62 had a laparoscopic Heller myotomy. The two groups were similar in demographic characteristics, symptoms and preoperative treatments. Intraoperative esophageal perforation occurred more frequently in the laparoscopic group (16% *vs.* 0%). The rates of relief of symptoms, and postoperative heartburn were similar after robotic and laparoscopic Heller myotomy after 18 and 22 months of follow-up. The results of these two studies suggest that the robotic approach decreases the incidence of esophageal perforation even in patients who had previous treatment. However, the poor quality of the studies limits the interpretation of these results.

Robotic excision of epiphrenic diverticula

The surgical approach for the treatment of patients with symptomatic epiphrenic diverticulum has radically changed during the last 20 years. To date, minimally invasive laparoscopic epiphrenic diverticulectomy with myotomy and fundoplication is the most popular surgical option since it is associated with excellent postoperative outcomes. However, it is a technically demanding operation and is burdened by high postoperative morbidity rates. A leak of the staple line is described in up to 23% of patients, pulmonary complications occur in up to 10% of patients; mortality rates reported in the literature vary between 0% and 7%. In addition, a thoracoscopic approach may be required to perform the diverticulectomy in those patients with a high upper part of the diverticulum that cannot be safely dissected with the rigid laparoscopic instruments tools or when there are severe adhesions between the diverticulum and the pleura.

During the last few years, a few case reports describing the feasibility and safety of the robotic approach have been published (17,18). Some authors have stated that the stereoscopic endoscope, the articulated robotic instruments, the 3-dimensional visualization, the robotic motion scaling and the tremor-filtering might help dissect the upper part of the diverticulum safely, minimizing the risk of injury to the pleura. In addition, the vision magnification may allow performing a safe myotomy up into the mediastinum, with reduced risk of mucosal perforation (17). However, the data currently available in the literature are very preliminary, the level of evidence very low and further studies are awaited to confirm the potential benefits of the robotic technology over the laparoscopic approach.

Robotic redo surgery

Laparoscopic redo surgery for recurrent hiatal hernia, failed fundoplication for GERD or recurrent dysphagia after

Heller myotomy is associated with increased morbidity when compared with primary surgery and less predictable functional outcomes. Currently, most cases are performed by an open approach (laparotomy or thoracotomy), while the laparoscopic approach is used in selected cases. Redo surgery is challenged by adhesions and inflammation of the anatomical planes that become much more difficult to be identified and dissected. As a consequence, complication rates and conversion to laparotomy of laparoscopic redo surgery significantly increase. The use of robotic technology in these patients might lead to better visualization of the surgical field with improved dissection of the planes and, subsequently, to reduced risk of intraoperative complications. A recent single-institution study by Tolboom *et al*. (19) included 75 patients undergoing redo surgery for recurrent GERD-related symptoms or dysphagia: 30 patients had standard laparoscopic redo surgery, while 45 patients had a robot-assisted procedure. A significantly higher number of patients having the primary antireflux procedure performed by an open abdominal approach were present in the robotic group. However, conversion to open surgery occurred more frequently during laparoscopic than robotic redo surgery (17% *vs*. 2.2%, P=0.035). Early postoperative complication rates were similar. Postoperative length of hospital stay was shorter after robotic surgery.

Long-term follow-up outcomes from large prospective comparative (randomized) studies are necessary to prove these preliminary data in support of the use of robotic systems in patients with failed antireflux surgery.

Robotic esophagectomy for cancer

Open esophagectomy is the gold standard for the surgical management of resectable esophageal cancer. However, it is technically challenging and is burdened by significant early postoperative morbidity, despite advances in surgical techniques and perioperative patient management. The optimal approach to esophageal cancer is still under debate. While transhiatal esophagectomy is advocated for the reduced postoperative cardiopulmonary complication rates, transthoracic (Ivor Lewis) esophagectomy is considered in many centers the preferred approach since it is associated with lower esophago-gastric anastomotic leak rates and it may lead to a more extended mediastinal lymphadenectomy. Furthermore, mortality rates do not differ in patients developing cervical or intra-thoracic anastomotic leak after esophageal resection performed in high volume centers.

The last 25 years have witnessed a slow increase in the implementation of minimally invasive approaches to esophageal cancer. Evidence from non-RCTs and small RCTs show that laparoscopic/thoracoscopic esophagectomy was associated with lower cardiopulmonary complication rates and early mortality, and shorter hospital stay than open Ivor Lewis esophagectomy. However, concerns about the technical complexity and oncologic adequacy have limited the adoption of the minimally invasive approach in patients with esophageal cancer.

More recently, robot-assisted thoraco-laparoscopic esophagectomy has been introduced aiming at overcoming the limitations and challenges of the conventional laparoscopic/thoracoscopic approach. To date, several case series and only a few comparative studies have been published, showing promising results in terms of both feasibility and safety of this approach. Ruurda *et al*. (4) published in 2015 a systematic review about robot-assisted esophagectomy for esophageal cancer. They included 16 papers, 5 of them (118 patients) reporting on the use of the robotic system for the abdominal dissection during a transhiatal esophagectomy. Conversion rate to open surgery ranges between 0% and 12.5%; anastomotic leak rates varies between 9% and 33%, and median hospital stay ranges between 9 and 11 days. The number of lymph nodes surgically removed varied between 15 and 22. The eleven studies that have assessed the role of the robotic technology in the transthoracic esophagectomy reported conversion rates up to 15%, anastomotic leaks in up to 38% of patients; median hospital stay ranged between 7 and 22 days. Cardiopulmonary morbidity rates did not significantly differ from those observed following open transthoracic esophagectomy. The number of lymph nodes harvested was as high as 43.

While the short-term outcomes from case series are encouraging, two studies comparing robotic and open esophagectomy or minimally invasive esophagectomy without robotic assistance failed to find differences in perioperative outcomes. Weksler *et al*. (20) compared 11 patients who had robot-assisted esophagectomy and 26 patients who had minimally invasive esophagectomy without the use of the robot. The two groups were similar in demographic characteristics and use of neoadjuvant treatments. Operative time, estimated blood loss and the number of resected lymph nodes were similar in the two groups. Also postoperative morbidity rates, the length of stay in intensive care unit and the length of hospital stay did not significantly differ. Also Yerokun *et al*. (21)

recently failed to find any clear advantage of the robot-assisted esophagectomy using population-level data. They compared perioperative outcomes and 3-year oncologic results obtained after open (n=2,958), standard minimally invasive esophagectomy without robotic assistance (n=1,077) and robot-assisted esophagectomy (n=231) for cT1-3N0-3M0 cancer of the middle or distal esophagus. Patients undergoing standard minimally invasive or robot-assisted esophagectomy had shorter hospital stay and more lymph nodes harvested than patients who had open surgery; however, no significant differences were observed in resection margin involvement, readmission and 30-day mortality. Three-year survival was also similar. The subgroup analysis of robotic versus standard minimally invasive esophagectomy found no differences between the two approaches in short-term and oncologic outcomes.

Some authors have speculated that the stable 3-dimensional view of the surgical field along with articulated surgical tools might help reach the upper mediastinum with better ergonomics, and allow a wide and precise dissection of the periesophageal tissues and the mediastinal structures thus leading to a higher number of lymph node harvested and possibly to higher rates of radicality in patients with large tumor (22). However, only limited short-term oncologic outcomes are available, and results from large RCTs with long-term outcomes like the ongoing ROBOT trial (23) are needed to validate the robotic approach for the surgical treatment of esophageal cancer. This is a single-institution superior trial comparing robot-assisted minimally invasive esophagectomy and open 3-stage transthoracic esophagectomy, with the hypothesis that robot-assisted esophagectomy has lower postoperative complications, less intraoperative blood loss and a shorter length of hospital stay, better quality of life and similar oncologic outcomes. A total of 112 patients with histologically proven and surgically resectable cT1–4 N0-3 M0 intrathoracic esophageal cancer are randomized to robot-assisted esophagectomy (n=56) or open 3-stage transthoracic esophagectomy (n=56). The primary outcome of this RCT is the rate of overall complications.

In conclusion, the use of the robotic technology to perform an esophagectomy for cancer seems to be safe and at least as effective as the open approach in the short-term. Potential benefits might come from future technological developments such as the integration of the robotic systems with advanced diagnostic imaging systems, including the fluorescence for the sentinel node biopsy and the image overlay for the identification of anatomical landmarks and the evaluation of the vascularization of the gastric conduit.

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Footnote

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Minimally invasive and robotic esophagectomy: state of the art

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Abstract: Esophageal cancer is the eight most common cancer in the world and surgical resection remains the gold standard not only in providing the optimal chance for cure but also the best palliation for dysphagia. Esophagectomy is a complex operation and is associated with significant morbidity and mortality that are reported as 23–50% and 2–8% in western country. At the moment no gold standard techniques exist for esophagectomy. The choice of the technique depends on several factors; location of tumor and surgeon's experience are probably the most relevant. Minimally invasive esophagectomy (MIE), performed in high volume centers, has shown to reduce the rate of complications with the same oncological outcome as open esophagectomy. The addition of robotic technique to MIE is relatively new and is gaining widespread acceptance. Robotic assisted minimally invasive esophagectomy (RAMIE) is safe and feasible, and its short-term results are comparable to conventional MIE. Randomized studies are needed to assess if there is any real benefit associated to the use of the robotic approach.

Keywords: Minimally invasive; esophagectomy; robotic assisted

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Introduction

Esophageal cancer is the eight most common cancer in the world and surgical resection remains the gold standard not only in providing the optimal chance for cure but also the best palliation for dysphagia. Esophagectomy is a complex operation and is associated with significant morbidity and mortality that are reported as 23–50% and 2–8% in western country (1). In the early nineties surgeons from all over the world started to have an interest in minimally invasive esophagectomy (MIE) and in finding a way to reduce the rate of complications (2). The results of these experiences were affected by the use of different surgical techniques but is now widely clear that mini-invasive approach reduces morbidity and mortality after esophagectomy. Patients operated with MI techniques reported better global quality of life, physical function, fatigue and pain at 3 months after surgery (3). Furthermore, in the last fifteen years, we have witnessed the rising of the robotic approach. However, if in some cases, such as prostatectomy, minimally invasive techniques are routinely used and the robotic approach is mandatory, in other cases the situation is completely different; this is the case of esophagectomy: only 15% of cases of esophagectomy worldwide are performed by using the conventional thoraco-laparoscopic or robotic approach (1). The aim of this paper is to review the available literature on MIE and robotic assisted minimally invasive esophagectomy (RAMIE) and check the advances in these techniques.

Literature search

PubMed database was searched for "minimally invasive",

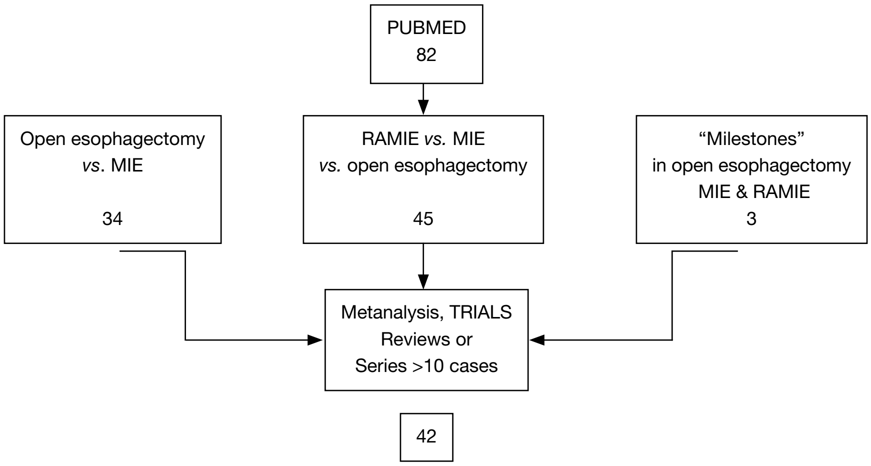

Figure 1 Flowchart search strategy.

"esophagectomy" and "robotic assisted" and their synonyms and abbreviations. No additional search software or special features were used. The search was limited to papers describing original patient data series >10 patients, written in English, ongoing or completed trials, reviews and meta-analyses. Three "milestone" studies have been quoted because they proposed innovative surgical techniques in open, mini-invasive and robotic assisted esophagectomy (2,4,5). The final search was performed on July 1st 2017. The investigators (M Taurchini and A Cuttitta) independently performed article and articles selection procedures. The results of the search and the selection process were summarized in a flow chart (*Figure 1*). Eighty-two studies were collected, out of which 42 were analyzed.

Open esophagectomy and minimally invasive techniques

At moment no gold standard technique exists for esophagectomy. The choice of the technique depends on several factors; location of tumor and surgeon's experience are probably the most relevant. Transthoracic esophagectomy (TTE) (Ivor-Lewis and McKeown TTE) remains the most used approach for the surgical management of resectable localized esophageal cancer. It provides a transthoracic *en bloc* esophagectomy with an extensive mediastinal lymph node dissection. Transhiatal esophagectomy (THE) has been proposed to reduce the high incidence of morbidity (4). Results from the comparison between TTE and THE have been controversial. Some reports have argued that transhiatal approach have a lower rate of complications whereas other scientific studies have demonstrated similar postoperative results and 5 years of survival rate (6,7) for the two approaches. In a published review by Verhage dated 2009 (8), ten case-controlled studies and one systematic review were retrieved. Data collection was grouped by surgical approach. Overall MIE data showed a decrease in blood loss (577 mL for conventional open surgery versus 312 mL for MIE) and reduction of hospital and ICU stay (19.6 and 7.6 versus 14.9 and 4.5 days, respectively). Total rates of complication were 60.4% for open esophagectomy and 43.8% for MIE. Pulmonary complications occurred in 22.9% and 15.1%. Mean lymph node retrieval was higher in MIE (23.8 versus 20.2). In 2012, 1,011 patients who underwent MIE for esophageal cancer, enrolled in a period of 15 years, were retrospectively considered by Luketich *et al.* to evaluate the postoperative outcome (9). He concluded that MIE is a feasible technique that reduces the incidence of perioperative complications and provide a quicker recovery, than open approaches, with a mortality rate of 1.6%. Nevertheless, he stressed the concept that MIE is a challenging surgical technique and that better results depend on each individual surgeon's experience and surgical volume. To date we have a couple of completed multicentric and randomized trials comparing MIE and open esophagectomy. The MIRO trial started in 2011. Two hundred patients were enrolled and randomly divided into a MIE group and an open esophagectomy group (the operation was an Ivor-Lewis esophagectomy). The results showed a significant reduction in the rate of perioperative pulmonary complications in the MIE group (10). Biere *et al.* (11) randomly assigned 56 patients to the open esophagectomy group and 59 to the

MIE group. In the first group 16 patients (29%) versus five patients (9%) in the second group developed pulmonary infection in the first 2 weeks; in the open esophagectomy group 19 patients (34%) against seven in the minimally invasive group, had pulmonary in hospital infection. One patient in the open esophagectomy group and two in the minimally invasive group died from aspiration and mediastinitis after anastomotic leakage. Other published works reported similar results (12,13). Furthermore, a few randomized trials are ongoing: the ROMIO trial is a three arm trial which aims at comparing the outcomes of total MIE versus hybrid MIE versus conventional open esophagectomy (Ivor-Lewis technique) (14). In the other two ongoing trials the Mc Keown procedure is being used (NCT02188615 and NCT 02017002). To date none of them has showed any results (15,16). In his paper published in 2015, Sihag *et al.* (17) retrospectively evaluated data on 3,780 data on 3,780 open esophagectomy and MIE, taken from the Society of Thoracic Surgeon Database. Comparable rates of morbidity and mortality between the two different approaches were reported but also a longer operation time and a higher rate of reoperation in the MIE group was observed. This rate of reoperation may reflect a learning curve. In fact, Osugy *et al.* in 2002 while he was examining from his experience, has determined that at least a number of 17 operations are required for a surgeon to acquire basic skills in thoracoscopic esophagectomy and 34 cases to obtain a similar or better postoperative outcome than that obtained through the open esophagectomy (18). A large meta-analysis (19) in 2015 of 13 studies with a total of 1,549 patients with resectable esophageal cancer was conducted and found that MIE does not compromise the long-term curative effect. In fact, the 2-year survival rate following the MIE is better than that following open esophagectomy. Incidence of anastomosis leakage was similar in the two groups, while greater operative blood loss was found in the open esophagectomy group. A very interesting survey was published by Haverkamp *et al.* in 2016 (20): the authors sent the survey to 1,118 members of the International Society for Diseases of Esophagus (ISDE), the World Organization for Specialized Studies on Diseases of the Esophagus (OESO), the International Gastric Cancer Association (IGCA). The questionnaire was filled out by 42% surgeons. Most of them (65%) worked in a University Hospital and in high volume centers (72%). The minimally invasive transthoracic approach was preferred in 43% of cases (especially in high volume centers). This percentage represents a three-fold increase in the number of respondents favoring minimally invasive techniques after the previous survey that was held in 2007.

RAMIE

The addition of the robotic technique to MIE is relatively new. Robot assisted thoraco-laparoscopic esophagectomy has been introduced to overcome the limitations of conventional MIE. In fact, especially the thoracoscopic step of the esophagectomy is really uncomfortable due to the 2D planar vision, the fulcrum effect through the thoracic wall and the use of non-articulated instruments. Magnified 3D vision, great maneuverability of "endo wrist" instruments, motion scaling, tremor filtration and a more comfortable surgeon position could be helpful in such as complex surgical procedure. Horgan *et al.* first described robotic assisted THE in 2003 (5). Since this first report, robotic assisted esophagectomy has being gained wider acceptance and wider consensus., In fact, Kumar and Bin Asa (21) in a personal review, published in 2014, collected 26 articles on the topic "robotic assisted esophagectomy" with total reported experiences of 295 procedures. The same indications and contraindications that are conventionally used for MIE are applicable to RAMIE. In the published literature are reported studies on all three types of esophagectomy: we may have robotic assisted transhiatal esophagectomy (RATE), robotic assisted mini invasive McKeown esophagectomy (RAMIME) and robotic assisted Ivor-Lewis esophagectomy (RILE) but the procedures are usually performed with hybrid approaches and the different techniques are difficult to compare. The abdominal step is often performed by means of the classic laparoscopic approach; in fact, the large area in the upper abdomen that needs to be dissected cannot often be reached with a robotic single docking position. The robot is usually very helpful during lymphadenectomy. In the thoracic phase of the operation, the patient is positioned in the left lateral decubitus, tilted 45° toward the prone position. The semiprone decubitus is usually preferred since conversion to thoracotomy is more easily performed than with the completely prone position. The robotic cart is brought to the table from the dorso cranial side of the patient. Some case reports or limited series in RAMIE (22-24) showed that robotic assisted esophagectomy was safe and feasible. These and further experiences in terms of number of cases, techniques, number of harvested lymph nodes, overall major perioperative complications rate and mortality rate

Table 1 Robotic minimally invasive assisted esophagectomy: technique and short results

Author	Number of cases	Technique	No. of harvested LN (mean)	Overall major complications (%)	Mortality rate (%)
Kernstine [2007]	14	McKeown	18	29	7.1 [1]
Boone [2011]	47	McKeown	27	44.6	6.4 [3]
Dunn [2012]	40	TH	19	67.50	2.5 [1]
Weksler [2012]	11	McKeown	20	36.4	NR
Sarkaria [2013]	21	McKeown/Ivor Lewis	28	24	4.8 [1]
de La Fuente [2013]	50	Ivor Lewis	20	28	2.0 [1]
Bongiolatti [2015]	8	Ivor Lewis	37	25	0
van der Sluiss [2015]	108	McKeown	26	34	3.7 [4]
Chiu [2016]	20	McKeown	18	10.5	0
Park [2016]	62	McKeown/Ivor Lewis	37	16	1.6 [1]
Cerfolio [2016]	85	Ivor Lewis	22	34	7.0 [6]
Okusanya [2017]	25	McKeown/Ivor Lewis	26	20	0

are resumed in *Table 1*. Kernstine *et al.* in 2007 (25) showed the first series of 14 RAMIME with a morbidity rate of 29%. In a 3-year single center experience by Dunn *et al.* (26) in 2012, 40 patients underwent RATE with an anastomotic leak rate of 25% (10/40) and anastomotic stricture rate of 67% (27/40) This high rate of complications improved in the last 20 cases with the growing experience acquired by the surgeon in performing RAMIE. Nowadays RAMIME and RAILE, as in standard MIE, replaced RATE in most cases. The transhiatal approach may be performed in critical patients considered too ill to undergo single lung ventilation (22,27,28). In 2012, Boone *et al.* (29) reported his personal experience in 47 RAMIME in a prospective study started in 2003 with an overall major morbidity of 46.5%. She showed a significative reduction in respiratory postoperative complications from 57% of the personal open esophagectomy series to 33% of the robotic assisted procedures. Subsequently other authors started to compare robotic approaches to conventional MIE. To date some comparative studies between RAMIE and conventional MIE are available. Weksler *et al.* (30) showed few differences in short terms outcome. In fact, postoperative morbidity rate, length of hospital stay and number of harvested lymph nodes were comparable in both groups of patients. Also, Yerokun *et al.* (31) has recently failed to find any clear advantage related to the use of the robot-assisted esophagectomy. He compared perioperative outcomes and 3-years oncological results obtained after open (2,958 procedures), conventional MIE [1,077] and RAMIE [231] for T1–3 N0–3 M0 cancer of the middle or distal esophagus. Patients undergoing standard mini-invasive or RAMIE had shorter hospital stay and more harvested lymph nodes than patients who received open surgery. However, no significant differences were observed in resection margins involvement and 3-year survival. In a prospective study by van der Sluis *et al.*, 108 patients with resectable esophageal cancer underwent RAMIE between 2007 and 2011 with a median follow up of 58 months. RAMIE was shown to be oncologically effective with a high percentage of R0 resection (95%) and allowed an adequate lymphadenectomy with a median number of 26 harvested lymph nodes. This is quite interesting especially if we consider that 78% of patients presented with T3–T4 disease and 65% of them had received neoadjuvant treatment. Conversion rate was 19% and 5-year overall survival was 42% (32). A randomized controlled trial to assess the real benefit of RAMIE versus open esophagectomy on long term outcome is absolutely needed. For this reason, the Utrecht group started the ROBOT trial (33) in 2012. As many as 112 patients with resectable T1–T4 N0–3 M0 intrathoracic esophageal cancer are to be enrolled in the study. As many as 56 patients will undergo RALE esophagectomy and 56 the open three-stage TTE. The primary endpoint is the rate of overall complications as stated by the modified

Clavien-Dindo classification of surgical complications (perioperative blood loss, postoperative complications, QOL). The secondary endpoint is recognized the length of ICU stay, length of hospital stay, mortality within 30 and 60 days and R0 resection rate. Definitive results of the study should be available by the end of 2017. Another interesting study was published by Okusanya *et al.* (34) who reported on 25 RAMIE cases enrolled since 2014 to 2016. Here, 72% of patients had previously undergone neoadjuvant therapy, 72% were adenocarcinomas and Ivor-Lewis esophagectomy was performed in 23 cases meanwhile in the other two a Mc Keown procedure was carried out. An R0 resection was obtained in 96% of cases and patients had a similar 30-day mortality, an anastomotic leakage rate, number of harvested lymph nodes and a conversion rate to conventional MIE patients previously reported. With the growing experience in this procedure, RAMIE can be helpful especially in patients with tumors in the upper mediastinum and with paratracheal lymph node metastasis. Okamura *et al.* (35) revealed the influence of anatomical factors on the difficulty of the thoracic procedure in MIE. A narrow upper mediastinum is an element predicting a thoracic procedural difficulty in MIE. The thoracic inlet is normally difficult to reach with an open or thoracoscopic conventional approach whereas the robotic system can reach this area without limitations and extends the operative and potentially curative options to these groups of patients. An adequate paratracheal lymphadenectomy along the laryngeal nerves is feasible during RAMIE according to the experience of a Korean group (36,37). The authors report the operative outcomes of robot-assisted thoracoscopic esophagectomy with extensive mediastinal lymphadenectomy for intrathoracic esophageal cancer. As many as 114 consecutive patients who underwent RAMIE with lymph node dissection along recurrent laryngeal nerve (RLN) followed by cervical esophagogastrostomy were enrolled in the study. The mean number of RLN nodes was 9.7±0.7. The most common complication was RLN palsy (26.3%), followed by anastomotic leakage (14.9%) and pulmonary complications (9.6%). The 90-day mortality was observed in three patients (2.5%). At multivariate analysis, preoperative concurrent chemoradiation was a risk factor for pulmonary complications. In extensive mediastinal lymphadenectomy, Broussard *et al.* (38) advises avoiding a monopolar electrocautery near the left/right mainstem bronchus. Unrecognized airway injury can lead to esophagotracheal fistula that is a devastating complication. In a recent retrospective study, Cerfolio *et al.* (39) analyzed personal experience in 85 Ivor Lewis esophagectomy (laparoscopic or robotic abdominal and robotic chest) from 2011 to 2015 and recognized a major morbidity rate of 36.4% and a 10.6% (9/85) overall operative mortality rate. Causes for these high rates were identified in anastomotic complications and wrong selection of patients. Therefore, corrective actions were taken. First, a stapled anastomosis was done in the following experience instead of the previous hand sewed one. Moreover, more attention was given to preoperative selection of the patients especially after neoadjuvant chemotherapy. Nutritional status and cardiopulmonary performance were carefully evaluated before surgery. In patients with an history of significative abuse of alcohol, a hepatic biopsy was always performed at the start of the operation and the planned surgery was aborted in case of cirrosis. However, the technical aspects of intrathoracic gastroesophageal anastomosis are quite difficult to explain. In fact, during Ivor-Lewis esophagectomy, it is very uncomfortable and difficult to perform a hand sewed anastomosis with conventional thoracoscopic technique even for very skilled surgeons. In RAMIE, the utilization of EndoWrist instruments, the deeper high definition 3D vision, the motion scaling and tremor filtration make a hand-sewn intrathoracic anastomosis possible and easier to accomplish. Trugeda and more recently Bongiolatti (40,41), published personal series of RAILE with hand-sewn intrathoracic esophagogastric anastomosis without increased incidence of leakage, stenosis or prolonged operative time. A published survey by Haverkamp *et al.* (20) shows that nowadays the preferred technique of anastomosis is to stapler the thoracic anastomosis and to hand-sew the cervical ones.

Conclusions

Esophagectomy is a complex and time-consuming procedure and it is associated with significant morbidity and mortality. As with other major procedures, surgeons have strived to increase the safety and efficacy of the procedure by employing minimally invasive techniques. Over the past 20 years, numerous papers regarding safety and efficacy of MIE were published, and it is clear nowadays that postoperative short and long-term results of conventional thoraco-laparoscopic MIE are similar to open esophagectomy. The role of robotic assistance is not well established, as this is more controversial. While direct clinical benefits to the patient may be difficult to clarify, benefits to the surgeon in terms of ease of the surgical performance and potential decrease in chronic work-related trauma and injuries may be significant. Another major challenge is to define what the robotic assistance is, since most of the reports on RAMIE use hybrid techniques using the robot only for some part of the procedure. It is therefore very difficult to compare the outcomes. In conclusion, robot-assisted resection for esophageal cancer is feasible, but a real benefit has not yet been demonstrated due to the limited number of randomized trials about RAMIE and lack of long-term oncological data (42). Despite its limitations and disadvantages there is little doubt that robotic assistance is here to stay. However, as esophagectomy is a challenging procedure teaching programs and proctoring are mandatory. As an example, a systematic teaching program in RAMIE at the Memorial Sloan Kettering Cancer Center in Pittsburgh started in 2014 and has reported excellent outcomes with increasing proficiency over the course of the surgeons' learning curve (34).

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Footnote

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Robotic assisted minimally invasive esophagectomy (RAMIE): the University of Pittsburgh Medical Center initial experience

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Introduction

Esophagectomy is the mainstay of therapy in appropriately selected patients with resectable malignant esophageal disease (1). However, esophagectomy remains a technically challenging procedure that has the potential for significant postoperative morbidity and mortality (2,3).

Over the last 20 years, minimally invasive esophagectomy (MIE) has become increasingly adopted as a means to potentially decrease the perioperative morbidity of these operations. At the University of Pittsburgh Medical Center (UPMC), MIE has been shown to be a safe and effective procedure with broad applicability and equivalent oncologic outcomes (4-6).

More recently, robotic assisted approaches to these operations have been increasingly described with early series reporting varying techniques and outcomes (7-12). Larger single institution series, including from Memorial Sloan Kettering Cancer Center and others, have reported systematic approaches in the development of a robotic assisted minimally invasive esophagectomy (RAMIE) program yielding excellent outcomes with increasing proficiency over the course of the learning curve (13-15). The primary purported benefit of the robotic assisted approach largely centers around the markedly increased control over the conduct of the operation afforded to the operator over open or alternative minimally invasive operations. The primary purpose of this study is to report the initial experience with RAMIE at the UPMC, a high volume teaching program with extensive experience in minimally invasive esophageal operations.

Methods

Patient selection

Between 2014 and 2016 patients seen for consideration of MIE were also considered for RAMIE. No specific selection criteria were specified, and patients considered appropriate for MIE were also considered appropriate for RAMIE. All patients underwent preoperative staging and evaluation including a full history and exam, esophagogastroduodenoscopy (EGD) with biopsy, fluorodeoxyglucose-18 positron emission tomography, computed tomography of the chest abdomen and pelvis and endoscopic ultrasound. Patients with suspected T3 or node positive tumors were referred for neoadjuvant chemotherapy or chemoradiation therapy and reevaluated for surgery following induction treatment.

The co-first author (I.S.S.), an experienced robotic thoracic surgeon including expertise in RAMIE, acted as primary or co-surgeon on the robotic console for all cases. The majority of cases were also performed with the senior author (J.D.L.), a highly experienced minimally invasive and esophageal senior surgeon, as co-surgeon. All cases were also assisted by surgical trainees who took part in various aspects of the case at the teaching console or bedside, as well as a single experienced physician assistant as the bedside operator. The same protocols used to manage the post-operative care of the MIE patients was used in the care of the RAMIE patients.

Data collection

This study was granted a waiver from the institutional review board (IRB) for retrospective study and review. Patient characteristics and outcomes were collected and recorded in prospective fashion in accordance with an ongoing esophageal surgery database. Postoperative complications and long term follow up was collected prospectively and retrospectively by chart review. Complications were graded using the Clavien Dindo Grading Score (16).

Operative technique

Abdominal approach

Our approach to RAMIE has been previously described by the co-first author, and was largely adapted from the MIE approach originally described and developed at UPMC (5,13). To summarize, EGD and bronchoscopy are performed at the beginning of every case. A midline 8 mm robotic port is placed at the level of the umbilicus. Three more 8 mm ports are placed in left and right mid clavicular line and at the left costal margins. A 5-mm non-robotic port is placed at the right costal margin through which a liver retractor is placed. A robotic bipolar forceps are used in the right midclavicular port, ultrasonic shears in the left midclavicular port and an atraumatic grasper in the leftmost costal port. An assistant 12 mm non-robotic port is placed in the right para umbilical position, as well as a second 5 mm assistant port further lateral in the same para umbilical line.

The dissection is generally begun with division of the lesser omentum, initial assessment and mobilization of the crura and esophageal hiatus, and exposure of the left gastric vascular pedicle. Complete celiac axis lymphadenectomy is performed, dissecting and sweeping all celiac, splenic and retrogastric lymphatic bearing tissues up along the vascular pedicle for later en bloc removal with the specimen. The left gastric and short gastric vessels are divided and the gastroepiploic arcade preserved in its entirety during gastric mobilization. Near infrared fluorescence imaging with indocyanine green may be utilized to clearly identify and preserve the gastroepiploic arcade to its termination point (15). In the setting of previous induction chemoradiation therapy, an omental flap based off of 2–3 omental perforating arteries may be harvested for later reinforcement of the gastroesophageal anastomosis. Complete gastric mobilization from the hiatus to the pylorus is performed. The gastric conduit is created with sequential applications of the endogastrointestinal stapler. The conduit is secured to the specimen for later traverse into the chest in proper orientation. The omental flap, if created, should be secured to the tip of the conduit to simplify transit into the chest as well.

A pyloroplasty is routinely performed in the majority of cases. The pylorus is open longitudinally with the ultrasonic shears and closed transversely with robotic suturing using interrupted sutures in a Heinicke-Mickulicz fashion. A feeding jejunostomy is placed and the abdominal portion concluded. The specimen is secured to the conduit and the abdominal portion is concluded.

Thoracic approach

The patient is placed in standard left lateral decubitus position. CO_2 insufflation is initiated with an entry needle just below the tip of the scapula. Eight mm robotic ports are placed at the eighth intercostal space at the posterior axillary line, the third intercostal space in the mid to posterior axillary, fifth intercostal place into the mid axillary line, and at the ninth intercostal space approximately in line with the tip of the scapula. An assistant non-robotic port is placed at the site of the diaphragmatic insertion. Complete circumferential esophageal mobilization is performed from the level of the hiatus to the azygous vein with careful attention to harvest all periesophageal lymph node bearing tissues en bloc with the specimen. During dissection of the subcarinal lymph node packet, great care must be taken to avoid energy associated thermal injury to the membranous wall of the airways. Judicious use of both bipolar energy sources and non-energy dependent sharp and blunt dissection, and clear visualization and exposure of the dependent anatomy are critical to avoid these injuries which may result in esophageal/conduit airway fistulas, a known pitfall of MIE, robotic or otherwise (7,13-14). Additional mobilization of the esophagus towards the thoracic inlet is completed with careful attention to avoid traction or direct injury to the recurrent laryngeal nerve. The conduit is delivered into the chest and sutured to the diaphragm. The caudal to cranial deep dissection along the contralateral pleura and left mainstem bronchus is completed with lateral retraction of the specimen once divided from the conduit.

The esophagus is divided approximately 2–3 centimeters above the azygos vein, although more proximal division may be performed dependent on the margins necessary.

A 4–5 cm access incision in made through the operator's "left" hand robotic working port to deliver the specimen out of the chest. A robotically placed running "baseball" suture is placed around the opening of the divided proximal esophagus, and the anvil of the 28 mm end to end anastomotic (EEA) stapler is inserted and secured. An additional reinforcing superficial purse string suture is placed to ensure tissue apposition around the stem of the anvil during deployment of the stapler. The EEA stapler is introduced through a gastrotomy site created in the proximal conduit tip, and the spike brought out through the lateral wall of the conduit ideally just above the level of the vascular arcade insertion. The stapler is then docked to the anvil and fired, creating the anastomosis, and the redundant conduit resected. If an omental flap has been harvested, it is loosely secured around the newly created anastomosis at this time. A drain is left posterior to the conduit and a chest tube is left in the right pleural space.

Per our post-operative pathways for non-complicated cases, patients are generally admitted to intensive care unit (ICU) on the day of surgery and discharged to step-down on postoperative day 1 or 2. Tube feeding is initiated on day 2. A barium swallow is performed after removal of the nasogastric tube on postoperative day 4–5 and a liquid diet initiated. Patients are discharged with the perianastomotic drain which is removed at the first postoperative visit if no evidence of anastomotic leak is observed.

Results

Patient demographics

Patient demographics and tumor characteristics are summarized in *Table 1*. Twenty-five patients underwent RAMIE from June of 2014 until October of 2016. The mean age of these patients was 67 years old with a range from 39 to 84 years. Eighty percent of these patients were male. Fourteen (56%) of these patient received neoadjuvant chemoradiation while four (16%) received neoadjuvant chemotherapy. Seven (28%) patients underwent RAMIE without previous neoadjuvant therapy.

Preoperative tumor characteristics

Eighteen (72%) of the patients underwent RAMIE for esophageal adenocarcinoma (ACC), six (24%) for squamous cell carcinoma (SCC), and one (4%) for adenosquamous carcinoma. The majority of patients presented with stage

Table 1 Patient demographics and tumor characteristics in 25 patients undergoing RAMIE

Variable	Value (range or %)
Median age	67 (range, 39–84)
Male gender	20 [80]
Induction therapy	
None	7 [28]
Chemotherapy	4 [16]
Chemotherapy and radiation	14 [56]
ASA risk class	
2	5 [20]
3	20 [80]
Approach	
Ivor Lewis	23 [92]
McKeown	2 [8]
Histology	
Adenocarcinoma	18 [72]
Squamous cell carcinoma	6 [24]
Adenosquamous carcinoma	1 [4]
Clinical stage	
IA	1 [4]
IB	2 [8]
IIA	4 [16]
IIB	2 [8]
IIIA	8 [32]
IIIB	6 [24]
IIIC	2 [8]
Pathologic stage	
0 (complete response)	4 [16]
IA	1 [4]
IB	2 [8]
IIA	2 [8]
IIB	6 [24]
IIIA	4 [16]
IIIB	4 [16]
IIIC	2 [8]

Table 1 (*continued*)

Table 1 (*continued*)

Variable	Value (range or %)
Pathologic T stage	
0 (full response)	4 [16]
In situ	1 [4]
1	4 [16]
2	4 [16]
3	12 [48]
N stage	
0	12 [48]
1	6 [24]
2	5 [20]
3	2 [8]
Completeness of resection	
R0	24 [96]
R1/R2	1 [4]
Angiolymphatic invasion	10 [40]
Perineural invasion	9 [36]
Median lymph node harvest	26 (range, 11–78)

RAMIE, robotic assisted minimally invasive esophagectomy.

IIIA or IIIB disease (32% and 24% respectively).

Operative variables

Perioperative outcomes and complications are summarized in *Table 2*. The median operative time (skin incision to skin closure) was 661 minutes with a range of 503 to 902 minutes. Median estimated blood loss was 250 cc. A mean number of 26 lymph nodes were harvested with a range of 11 to 78. There were 4 total conversions with 2 (8%) unplanned conversions. One conversion was to open laparotomy due to extensive intra-abdominal adhesions and the other to non-robotic minimally invasive surgery for routine thoracoscopic creation of the anastomosis.

Postoperative outcomes

The median length of stay was 8 days with a median

Table 2 Perioperative outcomes and complications in 25 patients undergoing RAMIE

Variable	Value (range or %)
Mean operative time (minutes)	661 (range, 503–902)
Median estimated blood loss (mL)	250 (range, 50–700)
Conversions (unplanned)	
To non-robotic MIS	1 [4]
To open	1 [4]
Median ICU length of stay (days)	2 (range, 1–10)
Median hospital length of stay (days)	8 (range, 6–20)
Complications (Clavien Dindo)	
Class I	3
Postoperative ileus	1
Urinary retention	1
Incisional cellulitis	1
Class II	16
Atrial fibrillation	6
Pneumonia	3
Pleural effusion requiring catheter drainage	2
SVT	1
Hyponatremia	1
Delirium	1
Decubitus ulcer	1
Chyle leak	1
Class IIIa	3
Respiratory failure requiring ICU readmission	1
Class IIIb	1
Respiratory failure requiring tracheostomy	1
Class IV	1
Endocarditis	1
Anastomotic leak ≥ grade 2	1 [4]
90 day mortality	0
Follow up time (months)	9.2 (range, 0.9–27.3)

RAMIE, robotic assisted minimally invasive esophagectomy.

Table 3 Comparative outcomes of minimally invasive esophagectomy (MIE) and robotic assisted minimally invasive esophagectomy (RAMIE)

Variable	Luketich 2012, MIE	Sarkaria 2013, RAMIE	Current study 2017, RAMIE
Patient number	1,011	21	25
Age, median	64	62	67
Histology, n [%]			
Squamous cell carcinoma	105 [11]	2 [10]	6 [24]
Adenocarcinoma	727 [76]	18 [85]	18 [72]
Other	179 [13]	1 [5]	1 [4]
Median operative time, minutes	NR	556	661
Median estimated blood loss, mL	NR	307	250
Adequacy of cancer resection			
Negative margins, n [%]	939 [98]	17 [81]	24 [96]
Median lymph nodes examined	19	20	26
Median hospital length of stay, days	8	10	8
Anastomotic leak, n [%]	26 [5]	2 (9.5)	1 [4]
30-day mortality, n [%]	17 [1.7]	0 [0]	0 [0]

ICU length of stay of 2 days. Eight (32%) patients had uncomplicated hospital stays. One patient (4%) suffered a grade 2 or greater anastomotic leak. All other complications are summarized in *Table 2*.

There were no deaths within the 30- or 90-day postoperative period. No patients were lost to follow up. The mean follow up time was 9 months with a range of one to 27 months. In 24 (96%) patients, a complete resection with microscopically negative margins (R0) was obtained. Four patients (16%) had complete pathologic responses after neoadjuvant therapy.

Discussion

This study represents our initial experience with RAMIE at the UPMC, and suggests that the safe introduction of these procedures can be accomplished with excellent outcomes in the setting of a high volume esophageal practice with surgeons already proficient in MIE and robotic surgery. Compared to a large series of over 1,000 patients undergoing MIE at the UPMC, RAMIE and MIE patients had similar 30 day mortality (0% *vs.* 2.8%), clinically significant anastomotic leak (4% *vs.* 5%), median lymph nodes harvested (27 *vs.* 21), conversion rates (8% *vs.* 5%), and R0 resection (96% *vs.* 98%) (*Table 3*) (4). RAMIE operative times were greater and likely represent an early learning curve phenomenon, similar to that observed early and subsequent series from Memorial Sloan Kettering Cancer Center reported by the current co-first author (I.S.S.) (7,14). Interestingly, this learning curve phenomenon did not appear to be attenuated with the presence of an experienced RAMIE surgeon, suggesting an institutional learning curve, at least for time, independent of the operating surgeon's alone. Other elements of the learning curve in the current series were decreased compared to the early MSKCC series, including rates of conversion (8% *vs.* 42%) and early rates of anastomotic leak (4% *vs.* 14%). Of note, there were no enteric-airway fistulas in this series, potentially representing the extensive accumulated previous experience of the senior surgeons in robotic.

There are several potential advantages to the robotic platform in these procedures. Tissue dissection in areas such as the hiatus and mediastinum, especially in patients with marked response to neoadjuvant therapy, may be facilitated by the superior optics and visualization, as well as instrumentation with multiple degrees of freedom, afforded by the robotic platform. The addition of a central camera, as well as an additional "assistant" arm, both under direct control of the surgeon, decrease the reliance on surgical assistants and greatly elevate the surgeon's control over the conduct of the operation. Technically challenging portions of the MIE operation with long learning curves, such as pyloroplasty and creation of the stapled anastomosis, may be greatly facilitated with robotic suturing capabilities. While direct clinical benefit to the patient may be difficult to quantify, the benefits to the surgeon in terms of ease and simplification of self-orchestrated operative performance, and potential decrease in chronic work-related trauma and injuries, particularly involving long and complex operations, may be significant. As a caveat beyond the scope of this study, the financial and cost implications of these procedures are not currently well delineated within a large university practice with multiple surgical service lines utilizing robotic platforms. These potential costs in contrast to the potential benefits merit additional study to quantitatively characterize.

While our early RAMIE data is naturally limited by its relatively low volume of cases, the initial results are encouraging and do not suggest a compromise in surgical and early oncological outcomes with inception of the program within a high volume esophageal center of excellence with expertise in MIE. These institutional traits may represent a “best-case” scenario for development of a RAMIE program, but also represent a limitation of the study in that it is not clear what the applicability of these findings may be to other centers with less *a priori* experience. Regardless of practice specific background, much care and consideration must be taken to balance the needs of training surgeons in these complex robotic procedures without subjecting patients to unnecessary or undue risk. Preclinical observation of cases, simulation and stylized curriculum based training at established robotic RAMIE programs, case proctorship, and careful and graded accumulation of RAMIE experience with a priority on maintaining patient safety and outcomes may all help promote successful navigation of the learning curve without recapitulation of recognized and preventable procedural pitfalls, morbidity, and mortality.

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None.

Footnote

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

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The benefits and limitations of robotic assisted transhiatal esophagectomy for esophageal cancer

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Abstract: Robotic-assisted transhiatal esophagectomy (RATE) is a minimally invasive approach to total esophagectomy with less morbidity but equivalent efficacy when compared with the traditional open approach. The robotic platform offers numerous technical advantages that assist with the esophageal dissection, which allows the procedure to be completed without entry into the thoracic cavity. The major criticism of the transhiatal approach is that it forfeits the ability of the surgeon to perform a formal lymphadenectomy, but this does not appear to affect long-term survival.

Keywords: Esophageal cancer; esophagectomy; robotic-assisted transhiatal esophagectomy (RATE); indocyanine green (ICG); fluorescence-guided surgery

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Introduction

Robotic-assisted transhiatal esophagectomy (RATE) was first described by Horgan *et al.* in 2003 as a minimally invasive alternative to open total esophagectomy (1). In contrast to the classic open technique, minimally invasive total esophagectomy has less morbidity and mortality and results in a shorter length of stay including a drastic reduction in ICU-level care. Other minimally invasive approaches use a combination of laparoscopic and thoracoscopic techniques, which carry these same advantages, however, the learning curve is steep and requires entry into the chest with single lung ventilation for exposure (2,3). The robotic platform offers superior three-dimensional optics, innovative multi-articulated instruments, the ability to perform fine manipulations within the confines of the mediastinum, and intraoperative assessment of graft and anastomotic perfusion with fluorescence angiography, which is why RATE has been the method of choice for total esophagectomy at our institution since 2006.

Operative technique

Our operative team consists of two surgeons, one an expert in minimally invasive and robotic surgery, the other an accomplished surgical oncologist who is well versed in the multiple techniques in total esophagectomy. Both surgeons evaluate the patients pre-operatively which includes endoscopic ultrasound for tumor depth as well as the presence of any lymph node metastasis. A PET-CT is also obtained to evaluate for metastatic disease. In overweight or obese patients, a 2 to 4 weeks bariatric liquid diet is prescribed in an attempt to reduce visceral and mediastinal fat and aid with visualization. Patients with locally advanced disease (T2 or greater or node positive) complete a course of chemoradiation prior surgery through our comprehensive cancer center. All patients receive an

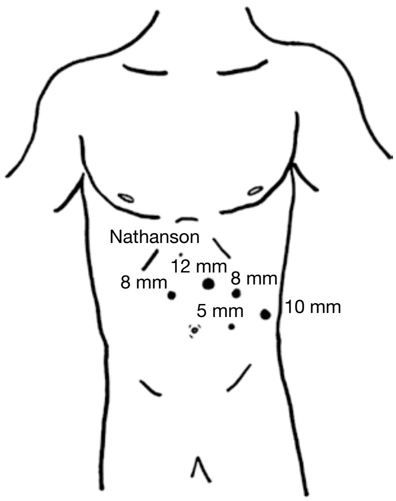

Figure 1 Trocar position for robotic-assisted transhiatal esophagectomy (RATE). The 8 mm ports are robotic trocars that double as the working ports for the laparoscopic portion of the case. The 12 mm port is a standard trocar that is used for the camera port, and the 5 and 10 mm ports are for the assisting surgeon to provide traction and suction.

upper GI endoscopy to once again directly visualize the lesion and assess for disease progression before proceeding with the case. Barring unanticipated progression of disease, the case is continued by the endoscopic injection of 200 units of BOTOX circumferentially into the pylorus to aid with postoperative gastric emptying (4). Pyloroplasty is not routinely performed.

The patient is positioned split leg on a beanbag device with heavy padded leg straps, which allows us to operate safely in a steep Trendelenburg position. Port sites are judiciously placed in a position that is optimal for both the laparoscopic and the robotic segments of the case. A 12-mm trocar is used for the robotic camera port and is positioned in the left upper quadrant just to the left of midline. Two 8-mm robotic trocars are placed in each the left and right upper quadrants which double as working ports for the laparoscopic portion of the case. A 10-mm assistant port is placed in the left lateral position, a second, 5 mm assistant port placed in the left mid-abdomen, and a Nathanson liver retractor is placed to aid with visualization and exposure (*Figure 1*).

We begin the procedure laparoscopically by mobilizing the greater curvature of the stomach and taking down the short gastric vessels with a laparoscopic ultrasonic scalpel. Care is taken to ensure the right gastroepiploic artery and tributaries are avoided to prevent ischemia to the tubularized gastric graft. The dissection is continued until the left crus encountered at which point the esophagus is dissected circumferentially off of the crura of the diaphragm and encircled with a Penrose drain, which is used by the assistant to aid with retraction. The dissection is continued along the lesser curvature until the left gastric artery is identified and divided with an endoscopic vascular stapler. The robot platform is then docked, coming in at a 45-degree angle over the patients left shoulder. Starting the case laparoscopically allows the surgeon to begin the dissection while the surgical technician and circulating nurse set up and drape the robot, maximizing time and efficiency in the operating room.

The primary surgeon then continues the case at the robotic console. The assisting surgeon remains scrubbed in as the bedside assistant to provide critical traction of the esophagus. The circumferential dissection of the esophagus proceeds proximally with care to include all periesophageal tissue and lymph node-containing fat. In the obese patient, visualization and exposure are considerably improved when the patient has been adherent to the pre-operative bariatric liquid diet. Many patients receive neoadjuvant chemoradiation, which can cause inflammation and scarring, making the plane of dissection between the esophagus and pleura difficult to discern. In the event that the pleura are entered, it is immediately repaired with either a clip or a running simple suture. We do not routinely place chest tubes, even when the pleura are entered, as carbon dioxide pneumothoraces without parenchymal lung injury are self-limited and hemodynamically insignificant in nearly all cases. The dissection is carried as proximal as possible along the esophagus taking full advantage of the multi-articulating instruments, tremor reduction, and three-dimensional visualization that the robotic platform offers while operating within the confines of the mediastinum. At the completion of the esophageal dissection the azygos vein will be clearly visualized to the right with the aorta to the left (*Figure 2*).

Upon completion of the esophageal dissection the robotic portion of the case is completed when the esophagus is fully dissected. The robot is undocked and the patient cart is positioned away from the operating field. The surgical oncology team begins the left neck dissection to access the cervical esophagus while the minimally invasive team prepares for the laparoscopic creation of the neoesophagus. Care is taken to preserve the recurrent laryngeal nerve during the cervical dissection. While the

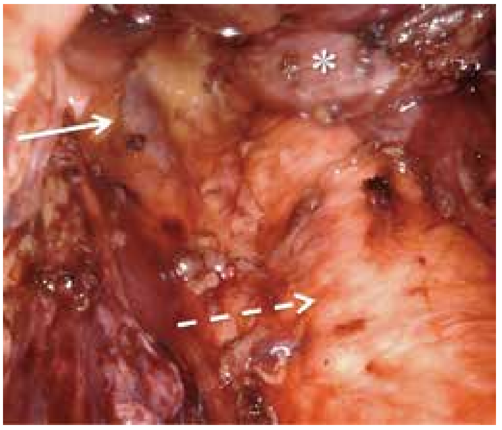

Figure 2 Representative view of the mediastinum during the robotic portion of the case. At the completion of the mediastinal dissection the esophagus (asterisk) is retracted anterolaterally and the azygous vein (solid arrow) is clearly visualized to the right and the aorta (dashed arrow) is to the left.

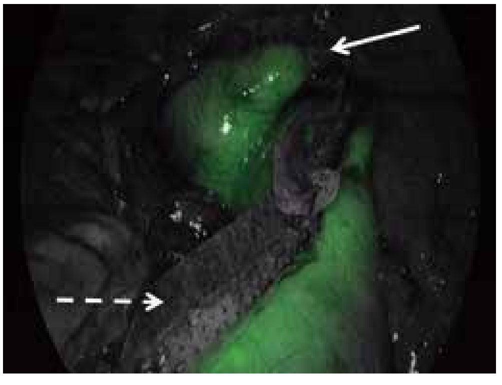

Figure 3 Representative image of indocyanine green (ICG) fluorescence angiography, which assesses the microperfusion of the tubularized gastric graft. The green represents blood flow and can be seen all the way to the tip of the graft (solid arrow). The dashed arrow shows the reinforced staple line.

neck dissection is underway, the minimally invasive team re-insufflates the abdomen and laparoscopically creates the tubularized gastric conduit that will become the neoesophagus. The stomach is divided along the lesser curvature with a linear endoscopic stapler that is reinforced with a layer of polyglycolic acid:trimethylene carbonate (PGA:TMC), a synthetic bioabsorbable copolymer. When completed, the tube measures approximately 6 cm in width. At this point the perfusion of the newly created tubularized gastric graft can be assessed with indocyanine green (ICG)

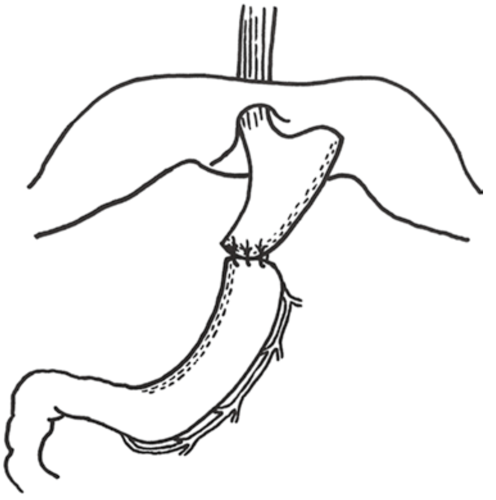

Figure 4 Schematic of the tubularized gastric graft that is sutured to the fully dissected esophagus and proximal stomach. Care is taken throughout the procedure to avoid damage to the right gastroepiploic artery, which will serve as the blood supply to the neoesophagus. The minimally invasive surgeon observes as the graft is pulled through the hiatus with care to ensure that the graft does not become twisted or kinked and is not under tension.

fluorescence angiography. The technique involves the intravenous injection of 7.5 mg of ICG and assessment of the microvascular perfusion along the length of the graft with one of several commercially available laparoscopes that have fluorescence capability (*Figure 3*). Special attention is paid to the proximal tip of the tubularized gastric graft. Any poorly perfused areas can be visualized and avoided during the creation of the cervical esophagogastric anastomosis.

The next step is to position the neoesophagus in the mediastinum and create a tension free cervical esophagogastric anastomosis. The fundus of the graft is sutured to the distal end of the resected specimen to assist with optimal positioning of the gastric graft without twisting or kinking (*Figure 4*). The surgical oncologist pulls the fully mobilized esophageal specimen through the cervical neck incision as the minimally invasive surgeon visualizes the specimen and tubularized gastric graft pass through the hiatus from below. The proximal aspect of the esophagus is divided and the side-to-side esophagogastric anastomosis is created and then oversewn with interrupted silk sutures. A Jackson-Pratt drain is left in place in the cervical neck incision and maintained until that patient is tolerating an oral diet without an increase in drain output.

Most patients are extubated in the operating room and

Figure 5 Supplemental video of key steps selected to demonstrate the advantages of robotic assisted transhiatal esophagectomy (5). Available online: http://www.asvide.com/articles/1138

transferred to either the ICU or the step-down unit at the surgeon's discretion for post-operative care. We do not routinely place jejunostomy feeding tubes. All patients complete an esophagogram on postoperative day 3, and if no extravasation is noted the patient is advanced to a liquid diet. Routine follow up with scheduled imaging studies is arranged for each patient to monitor for local recurrence and metastatic disease (*Figure 5*).

Discussion

Minimally invasive esophagectomy has been shown to have perioperative outcomes that are superior to the open approach without compromising survival (6). The physiologic demands of an open procedure significantly outweigh those of a thoracoscopic and/or laparoscopic approach, which is why we see a consistently shorter length of stay in patients who have had the minimally invasive approach. Further, fewer resources are utilized in the postoperative management of these patients since they typically require far fewer days in the intensive care unit and sometimes are even transferred to the step-down unit on the same day of surgery.

As is true for open esophagectomy, there are a variety of minimally invasive techniques available for esophagectomy. Regardless of the minimally invasive technique selected the dissection is challenging to learn and the robotic platform offers a significant teaching advantage when two consoles are available. The experienced surgeon can take a junior surgeon through the mediastinal dissection using on-screen visual cues to guide them through the often times challenging surgical plane, and take over when appropriate. Instruction during laparoscopic/thoracoscopic cases is reliant on verbal instruction, which can be considerably less effective. The learning curve for robotic over purely laparoscopic/thoracoscopic esophagectomy may therefore be lower.

The robotic platform has a number of features that are major assets during RATE. Because there are two closely spaced cameras, the operative field is displayed in three-dimension on the robotic surgeon's console, which gives the surgeon the added benefit of depth perception for superior surgical navigation. Control of the robotic instruments is also superior to laparoscopic or open for a number of reasons. First, the instruments have multi-articulating arms so they have increased rotational freedom over standard laparoscopic tools. As for control of the instruments, there is tremor reduction and adjustable motion scaling which allows for greater precision. There is also an improvement in ergonomics for the surgeon since the controls can be adjusted at any time back to the optimal operating position, and when the surgeon releases the controls the robotic platform will hold the position of the instruments steadily in place. All of these features make the robotic platform an outstanding option for performing fine manipulations in small spaces like the mediastinum. Further, the robot has built-in ICG fluorescent angiography technology for localization and preservation of the right gastroepiploic artery, and to check perfusion of the gastric conduit.

The robotic-assisted transhiatal approach avoids the need for routine entry into the pleural cavity, which itself has numerous advantages. Thoracoscopic approaches require right lung collapse and single lung ventilation, which can be problematic in patients with underlying lung disease. Further, postoperative pain and discomfort may be reduced in patients where thoracic access is avoided and chest tubes are not routinely placed. And finally, by placing the anastomosis high in the cervical esophagus, any potential leak will typically drain to the skin incision rather than into the chest and mediastinum as is the case with a mid-esophageal anastomosis. A full summary of the advantages to RATE can be seen in *Table 1*.

The major criticism of this approach is that fewer lymph nodes are retrieved than with a thoracic exposure where one can perform a formal lymph node dissection. The National Comprehensive Cancer Network guidelines recommend retrieving at least 15 nodes to appropriately stage a patient without neoadjuvant chemoradiation (7). Institutions performing RATE report obtaining at least this many nodes in published case series (8,9). Some series report increased

Table 1 Advantages of robotic assisted transhiatal esophagectomy

Teaching advantage
Decreased length of stay
Technical advantages
Improved 3D optics
Multi-articulated arms/instruments
Motion scaling
Tremor reduction
Built-in fluorescence angiography
Improved ergonomics
Eliminates thoracic approach
Anastomosis in neck (improved drainage access)

Table 2 Disadvantages of robotic assisted transhiatal esophagectomy

Unable to perform lymphadenectomy
Fewer lymph nodes
Cost of robotic procedure
Risk of conversion to open
Learning curve
Scheduling multiple surgeons
Not ideal for large or bulky masses
Risk of hemorrhage with limited access
Anastomosis in neck (venous congestion, graft ischemia)

survival with en-bloc dissections where more lymph nodes are presumably obtained (10), but a recent meta-analysis with over 1,300 patients undergoing a minimally invasive approach showed no difference (6). The robotic approach is also not ideal for large or bulky tumors, and should not be used in there is concern for involvement of other mediastinal structures.

An additional criticism is the need to place the anastomosis proximally in the neck as opposed to in the mediastinum. When compared to mediastinal anastomoses, cervical anastomoses are theoretically at higher risk for ischemia and tension due to the greater distance that the conduit must reach. Additionally, pulling the conduit up through the thoracic inlet can cause some degree of venous congestion that may impact anastomotic healing. For these reasons, some feel that the cervical anastomosis is at higher risk for leak or stricture than mediastinal anastomoses and prefer the latter. The flip side to this argument is that a cervical anastomotic leak much less morbid than a mediastinal anastomotic leak and can usually be managed conservatively with parenteral or distal enteral nutrition and continued drainage with the operatively placed drain.

A final drawback to this technique is the cost of using the robot and whether that cost is recouped by the benefits listed above. One obvious pitfall is in the case where the surgeon decides it is not safe to proceed robotically and the case is converted to open. In this scenario the case sustains all of the cost of a robotic procedure without any of the benefit. Additionally, as many of these cases are performed in busy tertiary care centers there may be high demand for block time for robotic cases. And finally, whenever there are two operating surgeons there can be the challenge of scheduling both surgeons for the same case. A summary of the drawbacks of RATE can be found in *Table 2*.

Patient selection for this technique is critical for it to be successful and to minimize the need for conversion to open. Patient body habitus is an important consideration. Whether open or robotic-assisted, the transhiatal approach is challenging in very tall patients or those with a long thorax. It can be very difficult to achieve communication between the proximal and distal dissection planes in these patients and access to the right chest may be required for a complete dissection. Similarly, patients with GEJ tumors extending down into the gastric cardia will require resection of a portion of the proximal stomach and the resulting gastric conduit may not reach the neck. In these cases the Ivor-Lewis technique with mediastinal anastomosis is required. A final consideration before embarking on RATE is surgeon experience and preparation of an appropriate operative team. It is critical to have an experienced minimally-invasive surgeon and surgical oncologist for this technique to be performed safely. Dissection in the mediastinum with the robot docked has the potential for significant bleeding with minimal exposure. A plan for rapid availability of blood products and rapid conversion to open must be in place and be well-understood by all team members.

Conclusions

In conclusion, RATE is a superior operation to the conventional open technique because it yields less perioperative morbidity while maintaining oncologic efficacy. The robotic platform offers numerous technical advantages over other minimally invasive techniques and can achieve a complete resection without entering the thoracic cavity. The major disadvantage of this technique is the inability to perform a formal lymphadenectomy, but this does not appear to have a deleterious effect on long-term oncologic outcomes.

As with open approaches, the choice of minimally-invasive technique for esophagectomy is likely to be dependent on surgeon experience and preference. RATE is an excellent option for well selected patients such as those with mid-to-distal esophageal tumors not invading adjacent structures and not extending into the proximal stomach, and those with underlying lung disease.

Acknowledgements

None.

Footnote

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

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Robotic esophagectomy

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Abstract: Robotic esophagectomy is an increasingly used modality. Patients who are candidates for traditional, open esophagectomy are typically also candidates for robotic esophagectomy. Knowledge of and training on the robotic platform is critical for success. Patient and port positioning is described. Either a hand-sewn or stapled intrathoracic anastomosis may be performed. Minimally invasive esophagectomy (MIE) appears to be associated with decreased respiratory complications versus open esophagectomy. Robotic esophagectomy may be performed with excellent perioperative outcomes, though long-term oncologic data regarding the operation are not yet available.

Keywords: Robotic; esophagectomy; minimally invasive esophagectomy (MIE)

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Introduction

The arrival of laparoscopic and thoracoscopic surgery in the 1980s paved the way for the first reported minimally invasive esophageal surgery in the 1990s. Minimally invasive esophagectomy (MIE), or MIE, refers to performing either or both the thoracic or abdominal portions of the case with laparoscopic or robotic assistance. Collard *et al.* first described esophageal resection by thoracoscopy in 1993 (1). This minimally-invasive approach documented shorter operative times, less blood loss, and shorter stays in the ICU with no increase in morbidity compared with the open approach (2). After the FDA's approval of The Da Vinci robotic surgical system for use in laparoscopy in 2000, Melvin *et al.* became the first to report robotic esophagectomy in 2002 (3). Since Melvin's pioneering operation, the use of robotic technology for esophagectomy has become increasingly common.

Indications

Indications for robotic esophagectomy parallel those of other MIE approaches: Barrett esophagus with high-grade dysplasia, end-stage achalasia, esophageal strictures, and esophageal cancer (4-8). While many T4 esophageal cancers are not amenable to surgical resection, selected patients have safely undergone en bloc resection of aorta or intrathoracic trachea or carina along with esophagectomy, but this would generally be a contraindication to robotic esophagectomy (9,10). Locally advanced cancers that are down-staged with neoadjuvant chemoradiotherapy are also amenable to robotic approach. Prior thoracic and abdominal surgery is not necessarily a contraindication but can certainly pose a greater challenge to the surgeon and should only be attempted in conjunction with the surgeon's comfort level. Robotic esophagectomy may allow surgeons to consider resection on somewhat older and more comorbid patients, as there is evidence to support a decreased perioperative complication rate, specifically respiratory complications (11). Early stage cancers (T1a and superficial T1b) can be managed with endoscopic mucosal resection (EMR). If a lesion is not amenable to EMR or is T1b or deeper on final pathologic analysis, esophagectomy should be considered. If EMR is performed in the context of Barrett's esophagus, radiofrequency ablation (RFA) to promote regression of the Barrett's should also be considered. Patients with persistent high-grade dysplasia after attempted RFA should also be considered for esophagectomy.

Equipment

The Da Vinci Surgical System is currently the only FDA-approved robotic system for lung surgery. The surgeon sits at a console some distance from the patient who is positioned on an operating table in close proximity to the robotic unit with its four robotic arms. The robotic arms incorporate remote center technology, in which a fixed point in space is defined, and about it the surgical arms move so as to minimize stress on the thoracic or abdominal wall during manipulations. The small proprietary Endowrist instruments attached to the arms are capable of a wide range of high-precision movements. These are controlled by the surgeon's hand movements, via 'master' instruments at the console. The 'master' instruments sense the surgeon's hand movements and translate them electronically into scaled-down micro-movements to manipulate the small surgical instruments. Hand tremor is filtered out by a 6-Hz motion filter. The surgeon observes the operating field through console binoculars. The image comes from a manoeuvrable high-definition stereoscopic camera (endoscope) attached to one of the robot arms. The console also has foot pedals that allow the surgeon to engage and disengage different instrument arms, reposition the console 'master' controls without the instruments themselves moving, and activate electric cautery. A second optional console allows tandem surgery and training. Da Vinci currently offers both the Xi and Si systems. The Xi system is newer and features an overhead beam that permits rotation of the instrument arms, allowing for greater flexibility in terms of direction of approach of the robot to the patient. Compared to the Si, he Xi also has thinner instrument arms, longer instruments themselves, and the option to switch the camera to any arm/port.

Preoperative evaluation

The preoperative evaluation is no different for robotic esophagectomy than for open or other forms of MIE. A history and physical exam focused on elements such as gastroesophageal reflux disease, Barrett's esophagus, achalasia and other motility disorders, prior surgeries, cardiac and pulmonary comorbidities, and functional status. Esophagoscopy should be performed to obtain the tissue diagnosis, rule out a synchronous secondary primary, as well as document location of tumor and presence of associated findings such as Barrett's esophagus. Bronchoscopy is necessary in all proximal and middle-third tumors to evaluate local airway invasion or a synchronous second primary. Endoscopic ultrasound locally stages the tumor by evaluating the depth of penetration and involvement of regional lymph nodes, also offering fine-needle aspiration biopsy of suspicious lymph nodes if necessary. PET-CT of the chest, abdomen, and pelvis fulfills the staging for distant disease.

Assuming no metastatic disease is present, the patient's cardiopulmonary function gets evaluated via pulmonary function and cardiac stress tests to ensure tolerance of single lung ventilation and carbon dioxide insufflation, which are typically employed during robotic esophagectomy. The patient's physiologic status should be improved preoperatively if necessary. Smoking cessation should be encouraged and alcohol use documented in order to screen for cirrhosis and anticipate possible withdrawal sequelae in the post-operative period. Induction chemoradiation is instituted for patients with nodal disease or T2 or greater penetration of tumor as noted from EUS. For patients undergoing neoadjuvant therapy, correction of malnutrition before surgery can markedly reduce the morbidity and mortality before resection. Patients with esophageal cancer who are obstructed or experiencing dysphagia will likely need assistance with nutrition pre-operatively during neoadjuvant therapy. Compared with enteral feeding with a feeding jejunostomy, oral alimentation after placement of a covered silicone stent results in better relief of dysphagia, higher performance status, better tolerance of chemoradiotherapy, and better quality of life (12-14).

After completion of neoadjuvant chemoradiotherapy, restaging PET-CT should be performed to rule out progression of disease or metastasis. Patients who have persistent disease or show a complete or partial response based on the lesion's FDG avidity on PET-CT are scheduled for esophagectomy 6–10 weeks after completion of neoadjuvant therapy. Lee *et al.* found that an increased time interval from completion of neoadjuvant therapy to surgery, while resulting in increased pathologic complete response rate, did not lead to an improved overall survival, and in fact, overall survival was worse when waiting greater than 64 days (15).

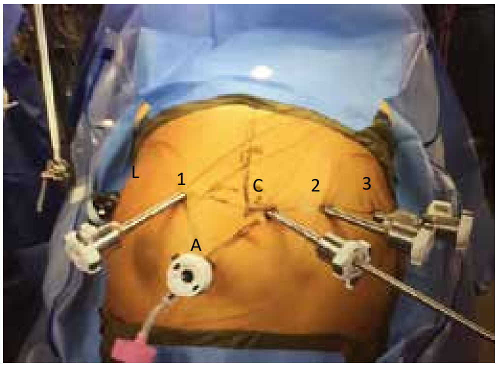

Figure 1 Port placement for the abdominal portion of procedure. [C] Camera port; [1] left robotic arm port; [2] right robotic arm port #1; [3] right robotic arm port #2; [L] liver retractor port; [A] assistant port.

Figure 2 Port placements for the thoracic portion of the procedure. [C] Camera port; [1] robotic arm 1, right hand; [2] robotic arm 2, 1st left hand; [3] robotic arm 3, 2nd left hand; [A] assistant port.

Patient positioning/port placement

Abdominal portion of procedure

The abdominal portion of the procedure is carried out via a robotic approach. The patient is placed in the supine position. At our institution, arterial and central venous lines are not typically used. A Foley catheter and nasogastric tube are placed, with special note to back all lines/tubes from the esophagus and stomach prior to stapler deployment. Both arms are tucked with foam padding at the elbow and wrist if body habitus allows. The patient should be secured to the operating room table with a large strap at the superior thigh and a foot board may be used to accommodate steep reverse Trendelenburg positioning.

Access to the abdomen can be performed by whatever means is comfortable to the surgeon. We use a Hassan technique and initially place a 12-mm camera port 18 cm inferior to the xiphoid process. We use a 30 degree down robotic camera. *Figure 1* shows the typical port placement for the abdominal phase of the operation. These should be spaced no more than 2–3 cm above the camera port and 9 cm apart. If the patients left side of the abdomen does not allow this due to space, the robotic arms may be staggered. If using the Xi system and robotic stapling is preferred, a 12-mm port should be placed for the left robotic arm. The two left upper quadrant ports should be 8-mm ports (if using Si system the 2nd port can be a 5-mm port). A 5-mm port is placed as close to the costal margin and laterally as possible to accommodate a liver retractor. We use a Snowden Pencer articulating pretzel retractor (Becton Dickinson; Franklin Lakes, NJ, USA). A 12-mm assistant port is placed in the patient's right lower quadrant, triangulated behind the left robotic arm port and camera port. This port is also used to deliver insufflation.

The preferred instrument selection is as follows: left robotic arm—Cadiere forceps, right robotic arm—vessel sealer, second right robotic arm- thoracic grasper (Si system) or tip-up fenestrated grasper (Xi system). If using the Si system, the operating room table is turned such that the robot can drive in over the patients head. The Xi system does not require the bed to be turned.

Thoracic portion of the procedure

At the completion of the abdominal portion of the procedure, while the patient is supine, a double lumen endotracheal tube is placed. The patient is then placed in the left lateral decubitus position. We do not use a bean bag for stabilization, but rather pad the patient with blankets/foam and secure the patient with cloth tape. A forward lean is desired to allow ideal access to the posterior mediastinum. The right lung is then excluded.

Figure 2 shows the port placement for the thoracic phase of the operation. The first port placed is the camera port which is placed 9 cm inferior and slightly posterior to robotic arm 1. Robotic arm 1 is placed just below the hair line of the right axilla in the anterior axillary line. A 5-mm port is initially used as the camera port (upsized to 8-mm or 12-mm for Xi and Si, respectively). A 5-mm 0 degree thoracoscopic camera is then inserted into the camera port to evaluate the pleural space for intra-thoracic adhesions and to visualize further port placement. Insufflation of

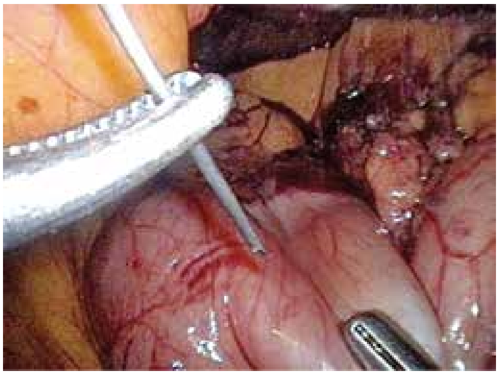

Figure 3 Botulinum toxin is injected into the pylorus (100 units in 4 mL of saline).

warm carbon dioxide is carried out to 12 mmHg which compresses the lung and lowers the diaphragm. It is important to carefully plan all four robotic port sites as this will minimize instrument collisions and limitations. We suggest using a ruler and marker to plan insertion sites. An 8-mm port for robotic arm 1 is then placed at the previously mentioned site. Robotic arm 1 serves as the surgeon's right hand. The next 8-mm port placed is for robotic arm 2. This incision is made 9 cm inferior to the camera port and slightly more posterior, tracking toward the right hip. Robotic arm 3 is a 5-mm port that is positioned 10 cm from robotic arm 2 as far posterior and inferior as tolerated. The final port placed is a 12-mm assistant port. This trocar should be triangulated with the camera and robotic arm 2 trocar anteriorly. The insufflation should be changed to this port as to not interfere with the robotic arms.

The preferred instrument selection is as follows: robotic arm 1 (right hand)—thoracic dissector with bipolar energy, robotic arm 2 (left hand)—Cadiere forceps, robotic arm 3—thoracic grasper (Si) or tip-up fenestrated grasper (Xi).

Conduct of operation

Abdominal portion of the procedure

The greater omentum is divided from the greater curve of the stomach by using the vessel sealer on the left side of the abdomen. The dissection is carried from the patients left to right until the pylorus is reached. Special caution is made to avoid injury to the right gastroepiploic artery. Attention is then turned to the short gastric arteries and continuing the dissection to the fundus. An omental flap should be preserved to be later used to wrap the anastomosis and protect the airway. The 2nd right robotic arm should be used to hold the colon/omentum in one direction while the assistant can hold gentle retraction on the stomach. Once the short gastric arteries are divided the retroperitoneal stomach attachments should be divided and the left side of the esophageal hiatus should be mobilized. The area beneath the esophagus should be as clear as possible to later facilitate encircling of the esophagogastric junction. The lesser omentum is then incised. The left gastric artery should be carefully inspected for an accessory or replaced left hepatic artery. Up to 12% of patients may have this anatomic variation (16). If encountered a clip may be placed and viability of the liver may be assessed. The left gastric artery is then ligated with a vascular stapler. Dissection is performed circumferentially around the esophagus and a few centimeters into the mediastinum. A 1 cm thick Penrose is then circumferentially placed around the esophagus and the ends secured together.

Botulinum toxin injection is then performed on the pylorus (*Figure 3*). We use 100 units in 4 mL of saline. Depending on surgeon discretion, pyloromyotomy or pyloroplasty may alternatively be performed. The pylorus should be able to reach the hiatus with minimal tension. The gastric conduit is then constructed using a linear stapler. We use a 4-mm staple height (45–60 mm length). The stomach is retracted laterally by the 2nd right robotic arm on the fundus and the assistant retracting the antrum. The stomach is not completely transected so that the specimen and conduit may be pulled into the chest. We typically place a suture in the distal portion of the staple line to easily identify it in the chest. A jejunostomy tube can be placed laparoscopically at this time if not placed preoperatively.

Thoracic portion of the procedure

With the bipolar thoracic dissector in robotic arm 1 (right hand) the mediastinal pleura is incised. Robotic arm 3 (2nd left hand) can retract the lung for exposure. The pleura are opened from the azygous vein down to the diaphragm (*Figure 4*). The inferior pulmonary ligament and associated nodal tissues are dissected free. The esophagus is dissected away from the aorta with special care to achieve hemostasis from perforating branches (*Figure 5*). This is typically done with bipolar energy and not clips. All paraesophageal tissue, including lymph nodes, should be dissected free from the diaphragm to thoracic inlet (*Figure 6*). Special considerations include harvesting subcarinal nodes, nodes adjacent to left and right main stem bronchi and careful

Figure 4 Posterior mediastinal pleural incised. [1] Robotic arm 1; [2] robotic arm 2; [E] esophagus.

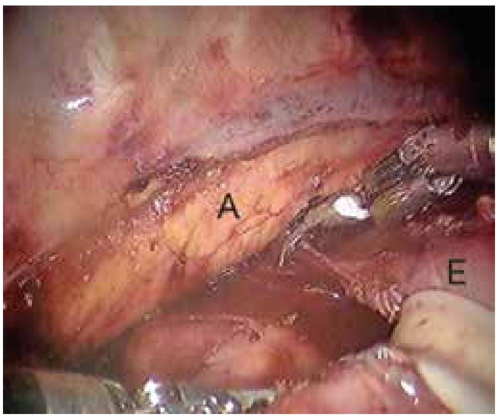

Figure 5 The esophagus is dissected off the aorta. All nodal tissue is removed en bloc. [A] Aorta; [E] esophagus.

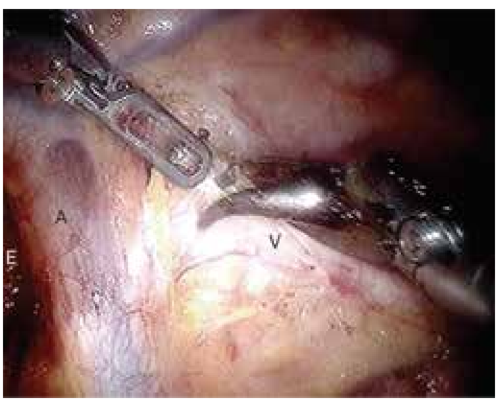

Figure 6 Dissection of paraesophageal tissue. [A] Azygous vein; [V] vagus nerve; [E] esophagus.

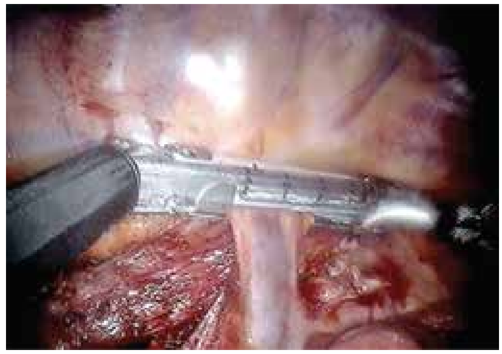

Figure 7 The azygous vein is stapled as posteriorly as possible.

attention to avoid thermal injury to the airway. Thermal injury may present as esophagobronchial fistula and can cause significant morbidity for the patient. The azygous vein is transected with a vascular staple load (*Figure 7*). We recommend transection as posterior as possible to avoid a long stump that may obstruct anastomosis creation.

Using the Penrose that was placed during the abdominal portion of the procedure the distal esophagus and gastric conduit are delivered into the chest. Bipolar scissors are then placed in robotic arm 1. While pulling distal traction the proximal esophagus is divided just above the azygous vein. The Cadiere forcep is then placed in robotic arm 1 and the assistant delivers the conduit further into the thoracic cavity. A stapler is then used to divide the specimen from the gastric conduit. The stapled edge of the conduit should be oriented laterally.

Silk sutures are then placed anteriorly and posteriorly from the conduit to the pleura to reduce tension on the anastomosis and maintain orientation.

Hand-sewn technique

In preparation of creating a double-layered esophagogastrostomy, atraumatic forceps are placed in robotic arm 2 and a suture-cut needle driver in robotic arm 1. Special note should be made to place the anastomosis as far away from the staple line towards the greater curve as possible. A row of interrupted 3–0 silk suture (10 cm long) is placed in the seromuscular layer along the "back wall" of the anastomosis. With the electrocautery a transverse gastrotomy is then made 2–3 cm in diameter on the posterior surface of the stomach and 5 mm away from the previously placed silk suture line (*Figure 8*). A 3–0 Vicryl is then placed at each corner of the anastomosis. Full-thickness purchases are

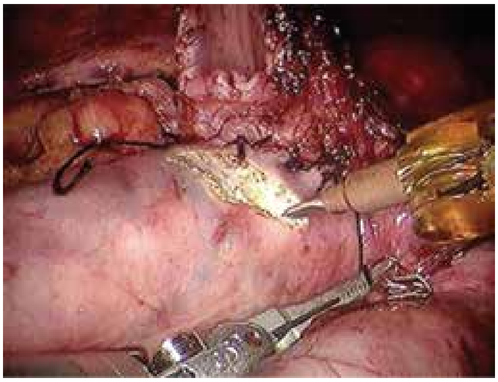

Figure 8 A back row of sutures are placed and the gastrotomy is made 5 mm from the suture line (hand-sewn technique).

Figure 9 Hybrid anastomotic technique for Ivor Lewis esophagectomy (17).
Available online: http://www.asvide.com/articles/1098

then made in a running fashion performing the “back wall” first. Prior to completion of the “front wall” the nasogastric tube is passed into the conduit under direct visualization. An additional row of 3–0 silk sutures are placed in an interrupted fashion on the “front wall” to complete the two layer anastomosis. If possible a piece of omentum is then delivered from the abdomen and buttressed between the conduit and airway and also covering the anastomosis. A suture is then placed at the right hemidiaphragm to the conduit to avoid herniation of abdominal contents into the chest. A hybrid technique involving stapling of the “posterior” wall of the anastomosis and hand-sewn “anterior” wall can also be performed (*Figure 9*).

Mechanical stapler technique

A purse string is created in the proximal esophagus. A 3–0 non-absorbable monofilament suture is used with special care to incorporate the mucosal layer. The anvil of the EEA stapler is placed in the esophagus and the purse string is tied. An additional purse string layer may be placed if there is concern for gaps around the anvil. A gastrotomy is then performed at the tip of the conduit. The EEA stapler is then placed through the gastrotomy. The tip of the stapler is then deployed through the superior/posterior wall of the conduit. Special care should be made to avoid multiple passes of the tip through the conduit and deployment of the tip into the aorta. The anvil and stapler tip and then connected and the stapler is fired. Careful inspection of the tissue in the stapler should show two complete rings of tissue. A linear stapler can then be used to close the gastrotomy.

A large specimen retrieval bag is then placed via the assistant port and the specimen is removed. One chest tube is placed posteriorly and toward the apex via robotic arm 2 port site. The ports are removed and insufflation discontinued, while inspecting port sites for bleeding. The lung is then re-expanded under direct visualization. The port sites are then closed (18).

Pearls/pitfalls

- The patient should be nutritionally optimized. Consider preoperative jejunostomy tube placement if the patient is losing weight or unable to maintain nutritional goals;
- Preparation and appropriate planning of trocar placement is key to avoid instrument collisions and frustration in robot docking;
- Be mindful of aberrant arterial anatomy. If there is concern for replaced left hepatic artery occlude the vessel and assess liver viability prior to ligation;
- Delivery of the gastric conduit into the chest should be performed by the assistant using a non-traumatic instrument (i.e., sponge forcep). Due to lack of haptic feedback on the robotic instruments, excessive force or traumatic handling of conduit is possible;
- Avoid monopolar electrocautery near the left/right mainstem bronchus. Unrecognized airway injury can lead to esophagobronchial fistula, a devastating complication.

Results

MIE with thoracoscopic assistance has been shown to be a safe and effective modality for esophageal resection (7). Biere and colleagues showed that VATS can reduce pulmonary complications after esophagectomy when compared to thoracotomy in a randomized controlled trial (19). The first series of robotic resections were performed by Kernstine *et al*. Fourteen patients were included in this series with good results. Anastomosis in this series was performed in the neck (20). Retrospective analysis by Weksler and colleagues showed that robotic esophagectomy was equivalent to thoracoscopic approach. Forty-three patients were reviewed and no difference was found in operative time, blood loss, number of lymph nodes resected, postoperative complications, days of mechanical ventilation, lengths of ICU stay or lengths of overall hospital stay (21). Survival data comparing open to thoracoscopic resection has historically been equivalent (22). As with the thoracoscopic approach, long term robotic survival data does not exist. In regard to anastomosis technique, no difference is noted between hand-sewn versus mechanical stapler technique, but there has been a trend toward increased stricture rate using the stapler technique (23,24).

In 2013 we reported our institutional experience for patients undergoing robotic esophagectomy with intra-thoracic anastomosis. Twenty-two patients underwent resection with no 30- or 90-day mortalities. Only three patients experienced minor morbidity which was related to urinary retention or atrial fibrillation. No patients underwent conversion to thoracotomy and only one patient required conversion from laparoscopy to laparotomy due to staple line breakdown. The median number of lymph nodes removed was 18 (range, 15–26). All patients received a pathologic complete (R0) resection (25). All 22 patients were alive at short-term (5 months) follow up and were without recurrence of disease. It is the author's beliefs that the robotic approach provides optimal visualization with a high-definition stereoscopic surgeon controlled camera, superior lymphadenectomy and a medium that is applicable to the open surgeon.

Conclusions

Robotic esophagectomy is a safe procedure that offers outcomes equivalent to thoracoscopic and open resection. Potential benefits of improved optics and lymph node dissection have yet to be determined, but are potential advantages of robotic resection.

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Footnote

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Transition from video-assisted thoracic surgery to robotic pulmonary surgery

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Abstract: The "da Vinci Surgical System" is a robotic surgical system that utilizes multi-jointed robotic arms and a high-resolution three-dimensional video-monitoring system. We report on the state of transition from video-assisted thoracoscopic surgery (VATS) to robotic pulmonary surgery, the surgical outcomes of robotic surgery compared to VATS, and the future of robotic surgery. Surgery utilizing the da Vinci Surgical System requires a console surgeon and assistant who have been certified by Intuitive Surgical, Inc., the system manufacturer. On the basis of the available medical literature, a robotic lobectomy has a learning curve that extends over approximately 20 cases for a surgeon who has mastered VATS. Surgery using the da Vinci System is safe, is associated with lower morbidity and mortality rates than thoracotomy, leads to shorter postoperative hospital stays, and ensures improved postoperative quality of life. Currently, no prospective studies comparing it to VATS have been conducted. The various studies that have compared robotic surgery and VATS have reported different results. At the present time, the benefits to patients of robotic surgery compared to VATS remain unclear. Areas in which robotic surgery may be superior to VATS include the superior operability of robotic surgery that improves safety and decreases the incidence of complication. To show that the costly robotic surgery is superior to VATS, prospective multicenter randomized studies need to be conducted. The da Vinci robot-assisted surgical system has already been highly evaluated for its safety, with recent studies reporting satisfactory outcomes. It remains necessary to verify whether the benefits to patients justify the higher cost of robotic surgery. Future developments in the field of robotic engineering will likely lead to the creation of systems that are even less invasive and allow for more advanced surgical techniques.

Keywords: Robot; minimally invasive surgery; thoracoscopy/VATS; robotics; lung

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Introduction

Video-assisted thoracoscopic surgery (VATS), in which surgery is performed with the use of an endoscopic camera that displays images of the surgical field on a video monitor, is currently being actively utilized as an alternative to a conventional open surgery (thoracotomy), which involves a 30-cm incision and cutting one or more ribs to gain access to the thoracic organs (1). However, a disadvantage of VATS is the fact that surgery is performed in a two-dimensional (2D) field because of the surgical field being viewed on a monitor, and the fact that the use of long, specialized instruments sometimes forces the surgeon to employ awkward surgical procedures. Thus, even now, a certain level of apprehension that VATS does not provide adequate surgical accuracy remains. As a result, many medical facilities have yet to adopt VATS for lung cancer cases. In addition, VATS utilizes rigid instruments, which makes it difficult for it to be employed in surgical procedures that require highly difficult suturing such as hand-closure of the bronchial stump, bronchoplasty, and pulmonary angioplasty. These types of surgical procedures are performed using highly invasive thoracotomy.

The "da Vinci Surgical System" (Intuitive Surgical, Sunnyvale, CA, USA) is a robotic surgical system that utilizes multi-jointed robotic arms and a high-resolution three-dimensional (3D) video-monitoring system. The merits of the da Vinci Surgical System include a true 3D binocular view and its multi-jointed forceps, which enable highly accurate surgical procedures. While performing surgery, surgeons are provided with a 3D image on an adjacent screen, which makes the surgeons feel as if they are actually within the thoracic cavity. In addition, the fact that the multi-jointed instruments are actually present within the thoracic cavity allows for a smooth and natural manipulation when performing surgical dissection. This is a major advantage over the conventional VATS technique that requires the use of straight instruments. Particularly in the case of lymph-node dissection, which requires accurate and finely detailed operations deep in the thoracic cavity, the 3D image and multi-jointed forceps of the da Vinci System allows the procedure to be performed much more easily than in conventional thoracoscopic surgery. Moreover, the da Vinci System compensates for physiological tremors of the hand, thus allowing minute manipulations to be easily performed.

Here, we report on the state of transition from VATS to robotic pulmonary surgery, the surgical outcomes of robotic surgery compared to VATS, and the future of robotic surgery.

Transitioning from VATS to robotic surgery

Currently, nearly all robot-assisted surgical procedures are performed using the da Vinci Surgical System. Here we describe the procedure for initiating the use of robotic surgery with this system.

The multi-jointed instruments and 3D view of the da Vinci Surgical System allow surgery to be performed in largely the same way as open surgery. However, when the surgeon manipulating the robot first starts to perform robotic surgery, they must have experience with VATS as it uses the same vessel-sealing device and stapler as well as the endoscopic surgical procedures and handling of bleeding as those used in thoracoscopic surgery are required. In addition, both the surgeon at the console and the patient side assistant must have a full understanding of the surgical procedures and robotic manipulation as well as procedures for handling unexpected situations such as vessel injury.

Surgery utilizing the da Vinci Surgical System requires a console surgeon and assistant who have been certified by Intuitive Surgical, Inc., the system manufacturer. Both the surgeon and the assistant must take the certification course offered by Intuitive Surgical, Inc. This course includes an online course for learning robot surgery, on-site training in the use of the da Vinci System at facilities that have adopted it, off-site training using either cadavers or pigs, and a clinical tour of a facility that utilizes the system. The da Vinci System also requires that the facility have one nurse or technician who has taken the certification course approved by Intuitive Surgical, Inc. as part of the staff. In addition, after deciding on the date that the first surgery is to take place, a training instructor certified by Intuitive Surgical, Inc. must join the surgeon, anesthesiologist, nurses, and technicians in the operating room and perform a da Vinci surgical simulation. To prepare for cases requiring emergency thoracotomy, training in emergency detachment ensures that they are able to detach the robot within 15 s. In cases in which there are no experienced individuals at the same facility, it is recommended that a surgeon who is thoroughly experienced in the field in question is invited to perform the first few operations to provide direct guidance in the surgical technique.

A surgical technique using the current da Vinci Xi Surgical System that I presently use is shown here. The patient is placed in the lateral decubitus position under general anesthesia, and a da Vinci surgical port is inserted above the fifth intercostal anterior axillary line using the surgeon's forceps. A 3-cm skin incision is then made above the sixth intercostal medial axillary line, and a GelPOINT Mini (Applied Medical, Rancho Santa Margarita, CA, USA) is affixed. This port was developed for single-port surgery, and 2–4 child ports can be inserted into the parent port to allow for CO_2 insufflation. The camera scope, which is the second arm of the da Vinci system, is inserted into a child port, and the surgical assistant provides assistance, such as aspiration, via a child port separate from the one through which the camera scope is inserted. A port is inserted above the seventh intercostal posterior axillary line and another is inserted more dorsally than the posterior axillary line of the seventh intercostal space. The third and fourth arms of the da Vinci System are inserted via these ports (*Figure 1*). Unlike the da Vinci S and Si Systems, the most recent Xi system does not require the da Vinci surgical cart to be docked adjacent to the patient's head. In VATS without the use of a robot, surgery is performed while standing on the right side of the patient regardless of whether the surgery is being performed on the left or right lung. As I ask the surgical assistant to stand on the right side of the patient,

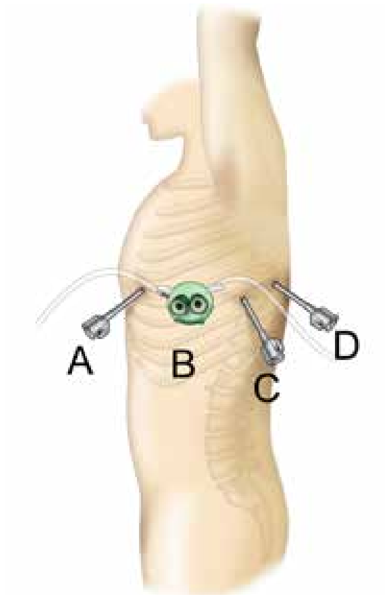

Figure 1 Placement of the da Vinci port for left lung cancer surgery. (A) A port held in the surgeon's left hand is inserted above the fifth intercostal anterior axillary line; (B) a 3-cm skin incision is made above the sixth intercostal medial axillary line, and a GelPOINT Mini (Applied Medical, Rancho Santa Margarita, CA, USA) is affixed for the camera scope and manipulations by the surgical assistant; (C,D) ports are inserted by the surgeon's right hand above the seventh intercostal posterior axillary line and more dorsally than the posterior axillary line of the seventh intercostal space. The two ports must be spaced at a minimum of 6 cm apart.

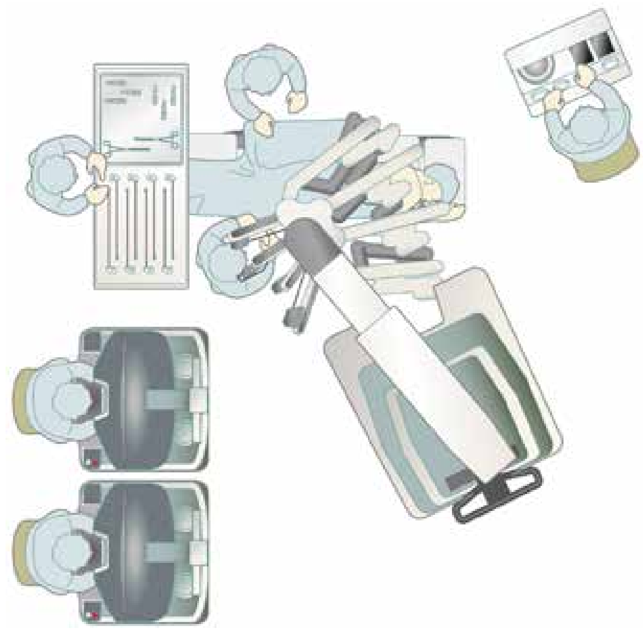

Figure 2 Placement of instruments during left lung surgery using the da Vinci Xi Surgical System. As the da Vinci surgical cart is docked to the side of the patient, the anesthesiologist can manage sedation from the patient's head without interfering with the da Vinci instruments.

which is the side that surgeons are accustomed to, I dock the da Vinci Xi surgical cart on the left side of the patient during surgery for either lung. The anesthesiologist is able to check the position of the endotracheal intubation tube and perform one-lung ventilation from the patient's head, similar to the manner in which routine VATS, thoracotomy, and open chest surgery are performed, by docking the Xi system to the patient's side (*Figure 2*). CO_2 is then insufflated into the thoracic cavity at 8 mmHg. The pressure from CO_2 insufflation causes the mediastinum to retract and reduces respiratory fluctuations of the mediastinum, which widens the thoracic cavity and thus makes surgical manipulations easier. The SurgiQuest AirSeal CO_2 delivery system (ConMed, Utica, NY, USA) is useful because it allows aspiration to be used even during insufflation. Traction of the lung is predominantly performed using the fourth robotic arm. I mainly perform surgical manipulations using bipolar fenestrated grasping forceps held in my left hand and bipolar Maryland forceps held in my right hand. The EndoWrist One Vessel Sealer (Intuitive Surgical, Sunnyvale, CA, USA) and the da Vinci stapler (Intuitive Surgical, Sunnyvale, CA, USA), which constitute an articulated vessel sealing system, can be used from a more natural direction that allows for safer surgery, with a higher degree of operability. This is a video representing left upper lobectomy performed at our hospital (*Figure 3*).

Learning curve for a robotic lobectomy

This leads to the next question—how many cases must the surgeon operate on before they are considered to have mastered robotic surgery? The learning curve is influenced by the surgical instrument settings and mastering of surgical techniques. Melfi *et al.* (3), Gharagozloo *et al.* (4), and Lee *et al.* (5) reported that the learning curve for lobectomy extends over approximately 20 cases. Meyer *et al.* (6) calculated that the learning curve for two surgeons experienced in VATS to master robotic surgery extends over 18±3 cases, on the basis of operative time, mortality, surgeon's comfort, and conversion rate. Jang *et al.* (7)

Figure 3 Left upper lobectomy using da Vinci Xi System (2). Available online: http://www.asvide.com/articles/1456

reported that there was a shorter learning curve for robotic surgery than for VATS. Considering that it is impossible to compare the transition of a surgeon who has performed thoracotomies to the first VATS with the transition of a surgeon who has mastered VATS to robotic surgery, it is difficult to compare VATS and robotic surgery. As with thoracotomy, robotic surgery allows a 3D view and also utilizes instruments with joints that mimic the joints of human fingers. Thus, it is expected that robotic surgery should have a shorter learning curve. However, as with VATS, both thoracotomy and robotic surgery involve unique surgical techniques that have to be mastered. On the basis of the available medical literature, a robotic lobectomy has a learning curve that extends over approximately 20 cases for a surgeon who has mastered VATS. However, in cases in which the surgeon has less than adequate experience with VATS, the learning curve will probably be longer.

Is robotic surgery more useful than VATS?

Surgery using the da Vinci System is safe, is associated with lower morbidity and mortality rates than thoracotomy, leads to shorter postoperative hospital stays, and ensures improved postoperative quality of life (8,9). Currently, no prospective studies comparing it to VATS have been conducted. Reports comparing the da Vinci System to VATS, such as the 2011 study by Jang *et al.* (7), reported less complication, less blood loss, and a shorter hospital stay. In addition, a 2012 study by Louie *et al.* (10) reported that patients required fewer analgesics and returned to daily activities earlier. In 2014, we analyzed 60 cases compiled from seven facilities in Japan. Although robotic surgery had a longer operating time, there were fewer postoperative complications and particularly fewer pulmonary complications than for VATS (11). In their 2014 analysis of the Society of Thoracic Surgeons (STS) database, Farivar *et al.* (12) reported a decreased length of stay in the hospital, 30 d mortality, and postoperative blood transfusion. However, in 2014 Swanson *et al.* (13) reported that a robotic lobectomy and wedge resection had a higher cost and longer operating time without any differences in adverse events. In 2014 Paul *et al.* (14) reported that in comparison to VATS, robotic surgery had a higher rate of intraoperative injury and bleeding (robot 5.0% *vs.* VATS 2.0%) at a higher cost. In their 2016 analysis of the STS database, Louie *et al.* (15) reported that in stage-I and stage-II cases a robotic lobectomy had more comorbidity and operative times were longer. In 2016, Cerfolio *et al.* (16) reported that vascular complications occurred in 15 out of 632 robotic surgery cases (2.4%) and concluded that it was possible to safely manage blood-vessel injury during robotic surgery.

A study of long-term outcomes by Park *et al.* in 2012 reported that in a multicenter study involving 325 patients, the 5-year survival rate was 80% (stage Ia 91%, IB 83%, and II 49%), which is a favorable outcome. Data showed that robotic thoracic surgery was safe and efficient and had a similar 5-year survival rate (17). In a 2017 comparison of long-term outcomes of a thoracotomy, VATS, and robotic surgery, Yang *et al.* reported that minimally invasive approaches to a lobectomy for clinical stage-I non-small lung cancer result in similar long-term survival as a thoracotomy. The use of VATS and robotics was associated with a shorter length of hospital stay and the robotic approach resulted in a greater lymph-node assessment (18).

The various studies that have compared robotic surgery and VATS have reported different results. At the present time, the benefits to patients of robotic surgery compared to VATS remain unclear. Areas in which robotic surgery may be superior to VATS include the superior operability of robotic surgery that improves safety and decreases the incidence of complication. A lymph-node dissection requires manipulation in deep regions of the body and robotic surgery facilitates and improves an accurate diagnosis of lymph-node metastasis which in turn leads to improved long-term outcomes. In addition, VATS procedures that utilize long, straight instruments place pressure on the thoracic wall and particular subcostal and intercostal nerves in particular, which causes postoperative nerve damage. In contrast, da Vinci surgery utilizes jointed instruments within the thoracic cavity, which makes it possible to avoid intercostal nerve compression and therefore decrease nerve damage.

To show that the costly robotic surgery is superior to VATS, prospective multicenter randomized studies need to be conducted. Robot systems are constantly being improved, and now even staplers are attached to robotic arms. It is necessary to investigate safety, pain assessment, incidence of complications, diagnostic accuracy of lymph node metastasis, and long-term outcomes of robotic surgery using several of the latest types of devices.

The future of robotic surgery in the field of pulmonary surgery

Even now, a large number of facilities use thoracotomy rather than thoracoscopy for cases of lung cancer. However, the major reasons that have prevented the widespread use of VATS in this field include the fact that the 2D VATS monitor does not allow a view that has depth, making it difficult to discern the field of view, and the use of long, straight instruments with no joints makes manipulation difficult. These technical drawbacks mean that many surgeons are apprehensive as to whether VATS can provide the same surgical accuracy as thoracotomy, resulting in it not being used in lung cancer surgery. However, the da Vinci System has managed to solve these technical issues, and as a result, robot-assisted surgical systems have the potential to become more widespread than thoracoscopic lung cancer surgery. Automatic suturing devices are commonly used to suture bronchus during VATS. This is because it is difficult to perform hand suturing in a natural direction using the long, straight, non-jointed instruments required by VATS surgery. However, in cases in which cancer develops in the bronchial center, it is necessary to close the bronchial stump and perform bronchoplasty in which end-to-end anastomosis is performed using hand suturing techniques. Insufficient accurate bronchial suturing can injure the bronchus and in turn cause postoperative bronchial stump fistula. However, the da Vinci System multiple joint instruments makes it possible to perform thoracoscopic suture closure of bronchial stump in a natural direction using minimally invasive surgery, when this technique was previously only possible using thoracotomy. As robotic surgery makes it possible to use highly advanced surgical techniques while remaining minimally invasive, it appears to be a formidable technique, especially for more difficult types of surgery.

In recent years, single-port surgery has come to be used in the field of pulmonary surgery (19,20). In contrast to robotic surgery, which aims to allow more advanced surgical technique to be performed with increased accuracy while maintaining the current low levels of invasiveness, single-port surgery aims to be even less invasive than current techniques. These surgical techniques are not only superior in terms of cosmetics, but are also less painful and less invasive than conventional multi-port VATS. However, considering that both the camera and the instruments are all inserted and manipulated via a single port, problems such as the instruments interfering with each other make surgical manipulations difficult. Recently, a da Vinci System that employs multi-jointed instruments via a single port has been developed. Once the use of this system becomes widespread, further development of robotic surgery can be expected. Because the techniques that can be accomplished by the human hand using VATS have already reached their limit, it is unlikely that further development can be made in this field. In contrast, as long as developments continue to be made in the field of robotic engineering, further development of robotic surgery can continue. In the near future, robotic surgery, which compensates for the weaknesses of conventional VATS, could actually come to replace VATS.

Conclusions

The da Vinci robot-assisted surgical system makes it possible to perform more accurate surgical techniques than conventional thoracotomy and thoracoscopic methods, and has a high potential for application to minimally invasive and highly advanced surgical techniques that cannot be performed using conventional VATS. It has already been highly evaluated for its safety, with recent studies reporting satisfactory outcomes. It remains necessary to verify whether the benefits to patients justify the higher cost of robotic surgery. Future developments in the field of robotic engineering will likely lead to the creation of systems that are even less invasive and allow for more advanced surgical techniques. We hope that in the future, robotic surgery, which is the latest advancement in medical technology, will be safely introduced into many medical facilities and benefit a large number of patients.

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Footnote

Conflicts of Interest: The author has no conflicts of interest to declare.

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Robotic lobectomy

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Abstract: Lobectomy is still currently the gold standard for treatment of lung cancer. With the great advancement of robotic surgery, robotic lobectomy has been demonstrated to be an operation that is safe and can be done in a timely manner, similar to video-assisted thoracoscopic surgery (VATS). Additionally, reports show that long-term oncologic outcomes for robotic lobectomy are consistent with those reported for VATS and open lobectomy. Patients are selected in the same manner as those for VATS. Improved optics, increased dexterity of the instruments, and better ergonomics can yield subjective advantages to the surgeon. The techniques of port placement, mediastinal lymph node dissection and the steps of each of the five lobectomies are important and described in the chapter, for both the da Vinci Si and da Vinci Xi platforms. The subtle differences are highlighted. Additionally, advantages of the platforms are discussed.

Keywords: Robotic; lobectomy; lung cancer; minimally invasive; lung resection

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Introduction

One of the first published reports of pulmonary lobectomy was by Drs. Norman Shenstone and Robert Janes from the Toronto General Hospital in 1932 (1). In their report, they described an open technique as "a long incision in the general direction of the ribs, passing just below the scapula," or via a thoracotomy. With modern advances in technology, surgeons have found techniques that decrease the size of incisions. Minimizing the invasiveness of pulmonary lobectomy has decreased postoperative morbidity, recovery time, and pain. Initially, minimally invasive lobectomy was performed using video-assisted thoracoscopic surgery (VATS) techniques. However, with the advent of the surgical robot-assisted techniques, the first robotic lobectomies were reported in 2003 by Morgan *et al.* and Ashton et al (2,3). Since then, the use of robotic technology for lobectomy has only grown. In 2015, over 6,000 robotic lobectomies were performed in the United States, and over 8600 done worldwide.

Initial evaluation

The evaluation of candidates for robotic lobectomy is similar to the evaluation of a patient for VATS or open. The same standard preoperative studies for any patient undergoing pulmonary resection are required. All patients require pulmonary function testing including measurement of diffusion capacity (DLCO) and spirometry. Patients with history of cardiac disease or have highs suspicion for cardiac disease should undergo a cardiac stress test.

If the resection is for suspected or biopsy-proven lung cancer, an oncological work up must be performed. Whole-body PET-CT scan is currently the standard of care. Mediastinal staging can consist of either endobronchial ultrasound guided fine-needle aspiration biopsy (EBUS-FNA) or mediastinoscopy, depending on expertise of the physician performing the procedure. A brain MRI may be ordered if concern exists for metastatic disease. Dedicated computed tomography scan with intravenous contrast or MRI can be performed if concern exists for vascular or vertebral/nerve invasion, respectively.

When it comes to assessing the ability of a patient to tolerate lobectomy from a respiratory point of view, the same criteria for VATS are used. It has been shown that VATS is safe in patients with a predicted postoperative forced expiratory volume (FEV1) or DLCO <40% of predicted (4). Currently the only absolute contraindications are our institution are vascular invasion, locally invasive T4 lesions, Pancoast tumors, and massive tumor (>10 cm). Other relative contraindications, such the need for reconstruction of the airway, chest wall invasion, presence of induction chemotherapy and/or radiation, prior thoracic surgery, and hilar nodal disease may not be absolute contraindications for robotic-assisted lobectomy for experienced surgeons.

Relevant anatomy/physiology

An intimate knowledge of the pulmonary anatomy and specifically, the relationship between hilar structures and their potential variations is needed to perform any lobectomy regardless of approach. Some discussion of the viewing angle does warrant discussion. In an open technique, the surgeon basically has two views of the hilum, the anterior or posterior direction. In VATS or robotic lobectomy, the camera approaches the hilum from an inferior direction. Retraction of the lung cam affect interpretation of the anatomy. Obviously, the spatial relationships between structures do not change, only the perception and visibility are adjusted. The surgeon must have a strong knowledge of what structures are at risk while performing each step and maneuver during the operation. This is the key to avoiding excessive blood loss, serious injury to structures and bad outcomes for the patient. Even more important, avoiding misidentification of structures and attention to aberrant or variable anatomy are also of paramount importance during robotic lobectomy. An injury to the wrong structure can force conversion to an open operation and negate the benefit of attempting minimally invasive surgery.

Conduct of operation

Patient positioning/port placement

Single lung ventilation is accomplished by placement of the double lumen endotracheal tube prior to positioning the patient. It is important check the ability to tolerate single lung ventilation prior to draping the patient, as repositioning the tube will be virtually impossible once the robot is docked. As with all lobectomies, positioning is in lateral decubitus position. Despite most surgeons' and anesthesiologists' beliefs, there is no need for axillary rolls and arm boards.

The robotic ports are inserted in differently depending on which model da Vinci robot being used. When using either robot, we mark the location of scapula, the spinous processes the entire length of the patients back and number the intercostal spaces. Port placement is dependent on system being used. Typically, for most resections, we place the ports in the 8th intercostal space. However, some surgeons may choose to place their ports in the 7th intercostal space for upper and middle lobectomies.

With the SI system, typical port placement for a right robotic lobectomy is as follows: robotic arm 3 is located two cm lateral from the spinous process of the vertebral body, robotic arm 2 is 10 cm medial to robotic arm 3, the camera port (we prefer the 12 mm camera) is 9 cm medial to robotic arm 2, and robotic arm 1 is placed right above the diaphragm anteriorly. All of these ports are typically placed in the same intercostal space. The assistant port is triangulated behind the camera port and the most anterior robotic port, and as inferior as possible without disrupting the diaphragm. The goal is to form the largest triangle possible to allow the assistant the most room to work. Transillumination of the ribs is helpful guide to finding the most ideal location for the assistant port and port 1. The robotic port 3 is a 5 mm port; port 2 is an 8 mm; camera port is a 12 mm; port 1 is a 12 mm; and the assistant port is a 12 mm.

For the Xi system, the ports are placed in slightly different locations. They are also numbered differently due to the system. Depending on the side of the operation, the ports are numbered differently. The following nomenclature applies for a right-sided lobectomy. Robotic port 1 is placed 4 cm away from the spinous process. Robotic port 2 is placed 8 cm from arm 1 and robotic port 3 is placed 8 cm from port 2. Robotic port 4 is placed right above the diaphragm anteriorly. The assistant port is triangulated behind the camera port and robotic arm 4 in a similar fashion. The camera is inserted into port 3. Ports 1 through 4 are all in the 8th intercostal space. The numbering of the ports is reversed for a left-sided lobectomy.

Exceptions to these arrangements are middle lobectomies, upper lobectomies with surgeon preference, and larger patients. Middle lobectomy ports differ in that the assistant port is placed more posteriorly, between the camera port and the left robotic arm. Additionally, the camera port may be better situated in some patients if it is located in the 7th intercostal space for upper lobectomies. In larger patients, the spacing between ports may be increased, but the placement of the most posterior port must remain the same.

A zero degree camera is used for all lobectomies. Insufflation of the camera or assistant port with carbon dioxide is used to depress the diaphragm, decrease bleeding, and compress the lung.

Mediastinal lymph node dissection

After examining the pleura to confirm the absence of metastases, the next step during our performance of robotic lobectomy is removal of the mediastinal lymph nodes, for staging and also to help expose the structures of the hilum.

- ❖ Right side: the inferior pulmonary ligament is divided. Lymph nodes at stations 9 and 8 are removed. The most posterior arm is used to retract the lower lobe medially and anteriorly in order to remove lymph nodes from station 7. Then, the most posterior arm is used to retract the upper lobe inferiorly during dissection of stations 2R and 4R, clearing the space between the SVC anteriorly, the trachea posteriorly, and the azygos vein inferiorly. Avoiding dissection too far superiorly can prevent injury to the right recurrent laryngeal nerve that wraps around the subclavian artery.
- ❖ Left side: the accessory arm (most posterior arm) is used the retract the lung anteriorly. The inferior pulmonary ligament is divided to facilitate the removal of lymph node station 9. The nodes in station 8 are then removed. Station 7 is accessed in the space between the inferior pulmonary vein and lower lobe bronchus, lateral to the esophagus. It is essential to dissect in plane anterior to the vagus nerve, so that the vagus is retracted toward the esophagus and the aorta. Finally, the accessory arm is used to wrap around the left upper lobe and pressed it inferior to allow dissection of stations 5 and 6. Care should be taken while working in the aorto-pulmonary window to avoid injury to the left recurrent laryngeal nerve. Station 2L cannot typically be accessed during left sided mediastinal lymph node dissection due to the presence of the aortic arch but the 4L node is commonly removed.

The five lobectomies

A key advantage of the robot is that the camera gives the surgeon the ability to change the view for greater than either VATS or open surgery can achieve. Due to this, structures may be isolated and divided in the order that the patient's individual anatomy permits and aids in a shorter operation. Below are descriptions of an outline of the typical conduct of each lobectomy.

Right upper lobectomy

- ❖ What is described below is a posterior technique starting with completion of the posterior fissure.
- ❖ Upon completion of the lymph node dissection, the 10R lymph node between the truncus branch and the superior pulmonary vein should be removed or swept up towards the lung, which exposes the truncus branch. During the lymph node dissection the arteries and veins should be dissected of off each other to facilitate safe encircling during the resection.
- ❖ The right upper lobe is then reflected anteriorly to expose the bifurcation of the right main stem bronchus. There is usually a lymph node here that should be dissected out to expose the bifurcation. This is key to both performing a right upper lobectomy or right lower lobectomy.
- ❖ The posterior fissure can be completed by identifying the main pulmonary artery and dissecting directly on its surface. Two key vascular structures should be identified at this step: the posterior segmental artery and the crossing vein that drains the posterior segment. Once identified, the path to completing the fissure can be found and performed with a stapler.
- ❖ The posterior segmental artery to the right upper lobe is exposed, the surrounding N1 nodes removed, and the artery encircled and divided.
- ❖ The right upper lobe bronchus is then encircled and divided. Care must be taken to apply only minimal retraction on the specimen in order to avoid tearing the pulmonary artery branches.
- ❖ Using the divided bronchus for retraction, the remaining arterial vessels should be exposed and can be divided individually or simultaneously, depending on the anatomy.
- ❖ With the completion of the arteries being divided, all that should be remaining is pulmonary veins. The bifurcation between the right upper and middle lobar veins is developed by dissecting it. The vein to the upper lobe can be divided.
- ❖ The anterior fissure can be completed with a stapler.

Right middle lobectomy

- ❖ Retraction of the right middle lobe laterally and

posteriorly with the most posterior robot arm helps expose the hilum.
- ❖ The bifurcation between the right upper and middle lobar veins is developed by dissecting it off the underlying pulmonary artery. The right middle lobe vein is encircled and divided.
- ❖ The fissure between the right middle and lower lobes, if not complete, is divided from anterior to posterior. Care should be taken to avoid transecting segmental arteries to the right lower lobe.
- ❖ The right middle lobe bronchus is then isolated. It will be running from left to right in the fissure. Level 11 lymph nodes are dissected from around it. It is encircled and divided, taking care to avoid injuring the right middle lobar artery that is located directly behind it.
- ❖ Dissection of the fissure should continue posteriorly until the branches to the superior segment are identified. Then the one or two right middle lobar segmental arteries are isolated and divided.
- ❖ Stapling of middle lobar structures may be facilitated by passing the stapler from posterior to anterior, to have a greater working distance.
- ❖ The fissure between right middle and upper lobes is then divided.

Right lower lobectomy
- ❖ The inferior pulmonary ligament should be divided to the level of the inferior pulmonary vein.
- ❖ The bifurcation of the right superior and inferior pulmonary veins should be dissected out. The location of the right middle lobar vein should be positively identified to avoid inadvertent transection.
- ❖ A sub-adventitial plane on the ongoing pulmonary artery should be established. If the major fissure is not complete then it should be divided.
- ❖ The right upper lobe is then reflected anteriorly to expose the bifurcation of the right main stem bronchus. There is usually a lymph node here that should be dissected out to expose the bifurcation. This is key to both performing a right upper lobectomy or right lower lobectomy.
- ❖ The superior segmental artery and the right middle lobe arterial branches are identified. If the superior segmental comes off early from the main pulmonary artery, it is isolated and divided, followed by the common trunk to right lower lobe basilar segments. It may arise more distally so that the right lower lobe artery may be taken with one staple. This can be done as long as this does not compromise the middle lobar segmental artery/arteries; otherwise, dissection may have to extend further distally to ensure safe division. Arterial division must preceded by proper identification of the middle lobe arteries and posterior segment of the upper lobe.
- ❖ The inferior pulmonary vein is divided.
- ❖ The right lower lobe bronchus is isolated, taking care to visualize the right middle lobar bronchus crossing from left to right. The surrounding lymph nodes, as usual, are dissected and the bronchus divided. As with the arteries, care to not compromise the middle lobe bronchus must be made.

Left upper lobectomy
- ❖ The presence of both superior and inferior pulmonary veins is confirmed, and the bifurcation dissected.
- ❖ As with the right sided resections, a thorough lymph node dissection opens up the posterior aspects of the dissection planes. Especially crucial is the removal of the level 10 lymph node that sits on the posterior aspect of the main pulmonary artery. This is accomplished by retraction of the left upper lobe anteriorly with most posterior robot arm helps expose the posterior hilum.
- ❖ Interlobar dissection is started, going from posterior to anterior.
- ❖ If the fissure is not complete then it will need to be divided. Reflecting the lung posteriorly again and establishing a sub-adventitial plane will be helpful. The branches to the lingula are encountered and divided in the fissure during this process. The posterior segmental artery is also isolated and divided. Division of the lingular artery or arteries can be done before or after division of the posterior segmental artery.
- ❖ The superior pulmonary vein is isolated then divided. Because the superior pulmonary vein can be fairly wide, it may require that the lingular and upper division branches be transected separately.
- ❖ Often the next structure that can be divided readily will be the left upper lobar bronchus, as opposed to the anterior and apical arterial branches to the left upper lobe. The upper lobe bronchus should be encircled and divided. Care is taken to avoid injuring the main pulmonary artery.
- ❖ Finally, the remaining arterial branches are encircled and divided.

Left lower lobectomy
- ❖ The inferior pulmonary ligament should be divided to the level of the inferior pulmonary vein. The lower

lobe is then reflected posteriorly by the most posterior robotic arm.

- ❖ The bifurcation of the left superior and inferior pulmonary veins should be dissected out.
- ❖ The lung is reflected anteriorly by most posterior robotic arm. The superior segmental artery is identified. The posterior ascending arteries to the left upper lobe are frequently visible from this view also. The superior segmental artery is isolated and divided. The common trunk to left lower lobe basilar segments may be taken as long as this does not compromise the middle lobar segmental artery/arteries; otherwise, dissection may have to extend further distally to ensure safe division. If the fissure is not complete, this will need to be divided to expose the ongoing pulmonary artery to the lower lobe.
- ❖ After division of the arterial branches, the lung is reflected again posteriorly. The inferior pulmonary vein is divided.
- ❖ The left lower lobe bronchus is isolated. The surrounding lymph nodes, as usual, are dissected and the bronchus divided.
- ❖ For left lower lobectomy, it may be simpler to wait until after resection is performed before targeting the subcarinal space for removal of level 7 lymph nodes.

Results

Robotic lobectomy can be performed with both excellent perioperative and long-term outcomes. At our center, we have a 30-day mortality rate of 0.25%, 90-day mortality rate of 0.5%, and major morbidity rate of 9.6% in patients undergoing robotic lobectomy and segmentectomy (5). Additionally, our median length of stay following robotic lobectomy is 3 days (6). Robotic lobectomy is equivocal to VATS in regards to blood loss, blood transfusion, air leak, chest tube duration, length of stay, and mortality when compared to traditional open technique (7-9). We have a <1% conversion rates to thoracotomy at our institution, but 3-5% is more typically reported[1]. Vascular injury is rare, and when it does occur, can occasionally be repaired without converting to a thoracotomy (10). Lymph node upstaging rates and 5-year survival for robotic lobectomy are comparable to lobectomy via thoracotomy and possibly improved versus VATS (11,12).

The one obvious disadvantage of the robotic approach when compared to VATS is cost. A robotic lobectomy can cost an additional $3,000–5,000 per case (13,14). This is due to multiple factors. First, the use of disposable instruments adds to the cost. Secondly, the sunk cost of the robot itself increases cost. Finally, there is a price for the maintenance plans required for employing the robot. Even with this additional cost, however, each robotic lobectomy yields an estimated median profit margin of around $3,500 per patient (15).

Conclusions

Robotic lobectomy has demonstrated as an operation that is safe and can be done in a timely manner. It can be done with superior perioperative morbidity and mortality outcomes compared to thoracotomy and similar to VATS. Additionally, reports show that long-term oncologic outcomes for robotic lobectomy are consistent with those reported for VATS and open lobectomy. Improved optics, increased dexterity of the instruments, and better ergonomics can yield subjective advantages to the surgeon.

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Footnote

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

Informed Consent: Written informed consent was obtained from the patient for publication of this manuscript and any accompanying images.

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Technique of robotic segmentectomy

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Abstract: Robotic segmentectomy can be a useful technique for patients with suboptimal pulmonary reserve, or for small peripheral stage I tumors. Port placement and conduct of operation is described for the various segmentectomies. Results for robotic segmentectomy are comparable to that for video-assisted thoracoscopic surgery (VATS) segmentectomy.

Keywords: Robotic; segmentectomy; lung cancer; minimally invasive; lung resection

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Introduction

Minimally invasive segmentectomy has traditionally been performed using video-assisted thoracoscopic surgery (VATS) techniques. The first robotic lobectomies were reported in 2003 by Morgan *et al.* and Ashton *et al.* (1,2). The first robotic segmentectomies were reported in 2007 by Anderson *et al.* (3).

Initial evaluation

The evaluation of candidates for robotic segmentectomy includes the standard preoperative studies for patients undergoing pulmonary resection. For patients with suspected or biopsy-proven lung cancer, whole-body PET-CT scan is currently the standard of care. Pulmonary function testing including measurement of diffusion capacity (DLCO) and spirometry is routine. Mediastinal staging can consist of either endobronchial ultrasound guided fine-needle aspiration biopsy (EBUS-FNA) or mediastinoscopy, depending on expertise. Certain patients may warrant additional testing, including stress test, brain MRI if concern exists for metastatic disease, and/or dedicated computed tomography scan with intravenous contrast or MRI if concern exists for vascular or vertebral/nerve invasion, respectively.

Segmentectomy is generally reserved for small (<2 cm) tumors with clinical N0 disease that are located in a position where removal via a segment rather than a lobe will not compromise the surgical margin. Lobectomy remains the favored approach for minimizing the risk of locoregional recurrence even for stage I lung cancers (4). Segmentectomy, however, can be utilized in patients for whom lobectomy is a less palatable option due to concerns about pulmonary function. Removal of a segment of lung rather than a lobe permits patients with worse preoperative pulmonary function to have values for predicted postoperative forced expiratory volume in 1 second (FEV_1) and diffusion capacity (DLCO) greater than 40%, which are considered safe thresholds in terms of perioperative risk (5,6). Furthermore, evidence that segmentectomy may yield equivalent outcomes to lobectomy in stage I lung cancers is accumulating (7,8).

Conduct of operation

Preparation

A well-trained team that communicates effectively is a priority for successful performance of robotic lobectomy. Criteria for a well-trained team include: documented scores of 70% or higher on simulator exercises, certificate of robotic safety training and cockpit awareness, weekly access to the robot, familiarity with the robotic and the instruments, and a mastery of the pulmonary artery from both an anterior and posterior approach. Currently, the Davinci surgical system console (Intuitive Surgical; Sunnyvale, CA, USA) is the only FDA-approved device

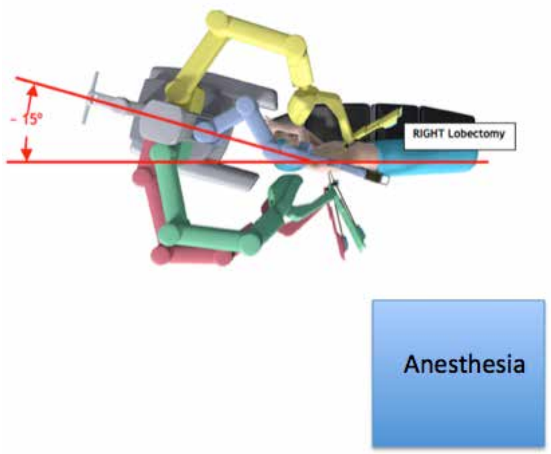

Figure 1 Location of robot, patient, and anesthesia for robotic segmentectomy.

Figure 2 Positioning for robotic segmentectomy.

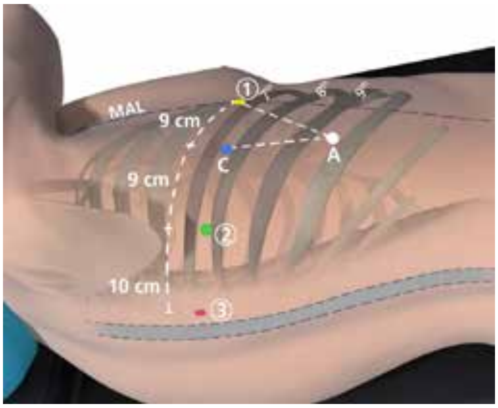

Figure 3 Port placement for robotic segmentectomy. The completely portal robotic segmentectomy with 4 robotic arms technique is shown. The circled numbers represent the robotic arms, C indicates the camera port, and A indicates the 15 mm access port. MAL, midaxillary line.

available for robotic lobectomy. Proper location of the robot should be established prior to the operation. The third robotic arm will need to be located so that it will approach the patient from the posterior. For the Si system, the robot is driven from over to patient shoulder at a 15-degree angle off the longitudinal access of the patient. The patient will need to be turned so that the axis of the patient is 90 degrees away from the typical position (i.e., head near the anesthesia workstation) to facilitate this (*Figure 1*). The use of long ventilator tubing and wrapping up this and other monitoring lines with a towel secured to the side of the bed is helpful to minimize interference with the surgeon/assistant. For the Xi system, the patient's head may remain near the anesthesia station, and the robot can approach the patient perpendicular to the direction of the bed. Precise placement of the double lumen endotracheal tube and the ability to tolerate single lung ventilation should be established prior to draping the patient, as repositioning the tube will be virtually impossible once the robot is docked.

Patient positioning/port placement

The patient is positioned in lateral decubitus position. Axillary rolls and arm boards are unnecessary (*Figure 2*). The robotic ports are typically inserted in the 8th intercostal space. Typical port placement is shown in *Figure 3* for a right robotic segmentectomy. The ports are marked as follows: robotic arm 3 (hereby referred to as the "accessory robotic arm") is located 2–3 cm lateral from the spinous process of the vertebral body, robotic arm 2 is 9–10 cm medial to robotic arm 3, the camera port is 9–10 cm medial to robotic arm 2, and robotic arm 1 is placed right above the diaphragm anteriorly. The assistant port is triangulated behind the camera port and the most anterior robotic port, and as inferior as possible without disrupting the diaphragm. We use a zero degree camera for this operation. Insufflation of the camera or assistant port with carbon dioxide is used to depress the diaphragm, decrease bleeding, and compress the lung.

Mediastinal lymph node dissection

After examining the pleura to confirm the absence of metastases, the next step during our performance of robotic segmentectomy is removal of the mediastinal lymph nodes, for staging and also to help expose the structures of the hilum.

- ❖ Right side: the inferior pulmonary ligament is divided.

Lymph nodes at stations 8 and 9 are removed. The accessory robotic arm is used to retract the lower lobe medially and anteriorly in order to remove lymph nodes from station 7. The accessory robotic arm is used to retract the upper lobe inferiorly during dissection of stations 2R and 4R, clearing the space between the superior vena cava (SVC) anteriorly, the esophagus posteriorly, and the azygos vein inferiorly. Avoiding dissection too far superiorly can prevent injury to the right recurrent laryngeal nerve that wraps around the subclavian artery.

- Left side: the inferior pulmonary ligament is divided to facilitate the removal of lymph node station 9. The nodes in station 8 are then removed. Station 7 is accessed in the space between the inferior pulmonary vein and lower lobe bronchus, lateral to the esophagus. The lower lobe is retracted medially/anteriorly with the accessory robotic arm during this process. Absence of the lower lobe facilitates dissection of level 7 from the left. Finally, robotic arm three is used to wrap around the left upper lobe and pressed it inferior to allow dissection of stations 5 and 6. Care should be taken while working in the aorto-pulmonary window to avoid injury to the left recurrent laryngeal nerve. Station 2L cannot typically be accessed during left sided mediastinal lymph node dissection due to the presence of the aortic arch but the 4L node is commonly removed.
- During performance of anatomic lung resections, removal of hilar, interlobar, and intersegmental lymph nodes helps facilitate dissection and permits individual pathologic analysis. If frozen section reveals the presence of malignancy in an intersegmental lymph node, the decision should generally be made to convert from segmentectomy to lobectomy assuming that the patient's lung function will tolerate it.

Right upper lobe posterior segmentectomy

The dissection of the hilum should be performed posteriorly after the lymph nodes in stations at levels 9, 8, and 7 have been removed. Then the level 11 lymph node between the right upper lobe and bronchus intermedius is removed. If this lymph node is positive for malignancy then a right upper lobectomy in the able patient. This identifies the posterior ascending artery, which can be absent in about 15–20% of patients. After identifying this artery from the back, which is possible in most patients, it can be divided. Then the posterior fissure between the right upper and lower lobes can be completed. With the lung retracted anteriorly by the accessory robotic arm, the bronchus is dissected more distally until the bifurcation is seen and the posterior segmental bronchus is encountered. This can then be isolated and divided. If the posterior ascending has not yet been taken (and it usually should be), it then is divided leaving only the vein. It is not necessary to take the posterior segmental vein but it can be seen in the fissure lying just superior to the pulmonary artery. The parenchyma is then stapled, separating the posterior segment from the remainder of the right upper lobe.

Right upper lobe apical segmentectomy

Posterior hilar dissection is performed as usual in order to obtain the level 9, 8, and then 7 and 11 lymph nodes. The lung is then retracted posteriorly by the accessory robotic arm. The visceral pleura overlying the upper lobe vein, truncus artery, and posterior ascending artery is divided. The upper lobe vein is dissected distally until the division of the apical vein becomes apparent. The apical vein is divided, exposing the truncus artery more fully. The branch of the truncus artery to the apex is then isolated and divided. With the lung still retracted posteriorly, the segmental bronchus to the apical segment is isolated and divided. All of these structures may be divided either via the assistant port or robotic arm 4 (Xi) or 1 (Si).

Left upper apical trisegmentectomy (lingula-sparing lobectomy)

Once the mediastinal lymph node dissection is complete, the area between the upper and lower lobes is dissected out posteriorly. This will reveal the posterior ascending artery, which can then be isolated and divided. This can be done from the assistant port, or with slightly more difficulty, from one of the robotic arms. The visceral pleura overlying the surface of the left main pulmonary artery as it comes out from under the aortic arch is divided, which should then reveal the anterior branches. The area between the anterior artery and the superior/posterior edge of the superior pulmonary vein is defined. The vein to the apical trisegment is then isolated anteriorly and divided. This can be done through the assistant port or from the robotic arm 3 (Xi) or 1 (Si). If the anterior artery is accessible at that point then it may be divided. However, usually the segmental bronchus to the upper division is stapled/divided first. This is identified by dissecting out the bronchus distally until the lingular bronchus is identified. As when performing a robotic left upper lobectomy, at times it may be easier to cut the segmental bronchus to access/divide the anterior branch of the artery, and then go back and staple it later. Once the airway has been divided, the left lung may be inflated, remembering to turn off insufflation first, in order to demarcate the segments. The parenchyma is then transected between the lingula and the apical trisegment.

Lingulectomy

The mediastinal lymph nodes, going from level 9, 8, 7 to 10L ad then 4L, 5, and 6. The fissure between the upper and lower lobes is first dissected out, in general from posterior to anterior. At times, if there is an incomplete fissure, the dissection may need to proceed from anterior, and a sub-adventitial plane developed so that the fissure above may be divided. The fissure can be divided with either ultrasonic energy or a stapler. The lingular arteries in the fissure are isolated and divided. This can be difficult due to the fact that the posterior ascending artery remain intact and therefore the pathway behind the lingular arteries that needs to be traversed is fairly narrow. This can be performed either via the assistant port, with proper retraction, or the left robotic arm. The superior pulmonary vein is dissected distally to expose the bifurcation of the upper division and lingular veins. The lingular vein may then be isolated and divided. This is done via the assistant port. Dividing the vein then exposes the left upper lobe bronchus, which again should be dissected out distally to identify the lingular bronchus, which is then isolated and divided (usually easiest from robotic arm 3). The parenchyma is then divided as described above for the left upper apical trisegmentectomy.

Superior segmentectomy

Either the vein or artery may be isolated first when performing a superior segmentectomy. For patients with a complete or nearly complete fissure, it is simple to dissect out, isolate and divide the superior segmental artery first. The lung may then be pulled anteriorly, and the posterior hilum dissected to extend the length on the bronchovascular structures. The superior segment vein should be visible, and can be isolated and divided next. This leave the superior segment bronchus. This may be approached either posteriorly or from the fissure. Reinflating the left lung can then help demarcate the superior segment from the basilar segments. The parenchyma may then be transected. The stapler may be deployed from the assistant port in most cases, though if a robotic stapler is available that can be used as well (in general from the left hand on a left sided superior segmentectomy and from the right hand on a right sided superior segmentectomy).

Basilar segmentectomy

In general it is simpler to use a vein-first technique when performing basilar segmentectomy. The ongoing vein to the basilar segments is isolated, taking care to preserve the superior segmental vein which should be visible as the most superior/posterior branch coming off of the inferior pulmonary vein. After division of the vein, the ongoing bronchus to the basilar segments should be visible. This is isolated, again taking care to avoid encompassing the superior segmental bronchus, which is going in a posterior/medial direction when viewed from the lateral decubitus position. Once the bronchus is divided, the ongoing arteries to the basilar lobes can usually be isolated and divided as a single structure. The fissure should be dissected out posteriorly to confirm that the superior segmental artery is being preserved. Ventilating the lung then demarcates the basilar segments from the superior segment, and this is divided with the stapler. The stapler may be directed from the assistant port, or in some cases via robotic arm 3 (Xi) or 1 (Si) on a left superior segmentectomy, and via the left robotic arm on a right superior segmentectomy (opposite that for a superior segmentectomy). If a single basilar segment is to be resected, dissection should proceed more distally in order to identify the relevant structures.

Results

Robotic segmentectomy can be done safely, with excellent perioperative outcomes and safety. Few conversions to thoracotomy may be anticipated. Our results are shown in *Tables 1,2*. Large series of robotic segmentectomy are summarized and compared to VATS segmentectomy in *Table 3*. Some surgeons have found that the operative time for robotic segmentectomy is longer than that for robotic lobectomy, and reported a slightly higher complication rate in terms of pleural space issues such as effusion and pneumothorax, but that has not been our experience (5). Although lower lobe sublobar resections appear to cause more of a decline in pulmonary function testing than upper lobe sublobar resections, these changes can recover by one

Table 1 Patient characteristics, N=100 patients for planned segmentectomy

Variable	Patients who had a robotic segmentectomy
Age years, median	71
Gender	
Male	50
Female	50
Ethnicity (n)	
White	88
Black	11
Other	1
BMI, median (range)	27.2 (16.6–38.9)
Type of segmentectomy	
LUL	46 (1 converted to lobectomy)
Lingulectomy	6
Anterior segment	4
Apical segment	7
Posterior segment	28
LLL	15 (1 converted to lobectomy)
Superior segment	14
RUL	19 (1 converted to lobectomy)
Posterior segment	16
Apical	2
RLL	20 (4 converted to lobectomy)
Superior segment	13
Basilar segment	2
Posterior segment	1
Final pathology for—patients with lung cancer (N=79)	
T1aN0M0	56
T1bN0M0	14
T2aN0M0	9
Histology of primary lung cancer	
Adenocarcinoma/lepidic pattern	5
Adenocarcinoma	34
Adenocarcinoma + small cell carcinoma	1
Small cell carcinoma	1
Squamous cell carcinoma	29
Large cell neuroendocrine tumor	9
Lung metastasis cell types	10
Breast	1
Melanoma	1
Prostate	1
Pancreas	2
Endometrioid	1
Colon	4
Smoking history	Yes (87%)
Forced expiratory volume in 1 s, median [range] (%)	74.5 [28–150]
Diffusing capacity of lung for carbon monoxide, median [range] (%)	67 [25–138]
Neoadjuvant therapy	
Preoperative chemotherapy	1
Preoperative radiation	1
ENB tattooing	16
Comorbidities (yes %)	
Hypertension	65
Diabetes mellitus	11
Congestive heart failure	4.5
CAD, stent	29
Pulmonary hypertension	2
Hyperlipidemia	41
COPD	37

BMI, body mass index; LUL, left upper lobe; LLL, left lower lobe; RUL, right upper lobe; RLL, right lower lobe; ENB, electromagnetic navigational bronchoscopy; CAD, coronary artery disease; COPD, chronic obstructive pulmonary disease.

Table 2 Patient outcomes

Variable	Patients who had a robotic segmentectomy (N=100)
Intent to undergo robotic segmentectomy	100
Surgery started and ended robotically	100
Patients converted to lobectomy	7
Operative time [minutes (range)]	88 [46–205]
Median measured blood loss (in cc.)	20
Minor post-op complications	
Pneumothorax	5
Atrial fibrillation	7
Coagulopathy	1
Major post-op complications	
Pneumonia	2
Length of hospital stay, median [range] days	2 [1–9]
Median follow-up of patients with cancer	30 months
Recurrence of cancer in ipsilateral lobe	3/89 (3%)

Table 3 Series of robotic and VATS segmentectomy

Study	Type	No. of patients	Mean op time (min)	Post-op complications (%)	LOS	60-day mortality	90-day mortality
Cerfolio (9)	Robot	100	88	2.0	2	0	0
Dylewski (10)	Robot	35	180*	11.4	3*	0	NA
Pardolesi (11)	Robot	17	189	17.6	5	0	NA
Toker (12)	Robot	15	84±26**	19.0	4±1.4	NA	NA
Yang (13)	Robot	35	146	11.4	2	0	NA
Demir (14)	Robot	34	76±23**	24.3	4.65±1.94	NA	NA
Demir (14)	VATS	65	65±22	0–1.5	6.16±4.7	NA	NA
Schuchert (15)	VATS	104	136	26	5	NA	NA
Gossot (16)	VATS	117	181±52	11.7	5.5±2.2	NA	NA

*, included lobectomy and bilobectomy operations; **, reported as mean console time. VATS, video-assisted thoracoscopic surgery; op, operation; LOS, length of stay; NA, not available.

year postoperatively (17).

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Footnote

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Pulmonary Surgery

Subxiphoid port applied to robotic pulmonary lobectomies

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Introduction

Despite the lack of randomized clinical trials, minimally invasive thoracic surgery has without doubt significant potential benefits for patients who require a lung resection when compared with traditional surgery. Robotic lung surgery has established its role in the last ten years thanks to the work of pioneering surgeons who applied this technology for the treatment of thoracic conditions (1-5). Cerfolio *et al.* (1) compared complete portal 4-arm robotic technique with rib-nerve-sparing thoracotomy for pulmonary lobectomy. They concluded that the robotic approach offers the same pathological outcome with fewer post-operative complications, lower mortality, shorter length of stay and improved quality of life. Park *et al.* (6) had a wide experience in the treatment of early stage lung cancer since 2001 and stated that the oncological outcome is similar to VATS or open pulmonary lobectomy.

Robotic surgery can offer a magnified 3D view which is superior to 2D endoscopic cameras on the market, which may improve the patient's outcome due to more accurate dissection and lymphadenectomy. The other advantages are the instruments' degree of articulation, the operator's comfort, being able to perform long procedures, resting their arms on the console, and the filtration of operator tremor. The main relative disadvantages are the cost, the learning curve and consequently the operative time. Some authors raised concern regarding the distance between the surgeon and the patient3. The robot is available in few centers and when present is usually shared within different surgical specialties with more difficulties to have enough training. In our department, we had chance to start a programme for robotic thoracic surgery in 2014 with a Da Vinci Si.

Parallel to the development of robotic surgery VATS surgery has also developed considerably. Born 25 years ago, in the early nineties, VATS lobectomy developed from the application of thoracoscopy, which was until then used for diagnostic procedures, to perform major lung resection (7). This evolved during the years into other approaches, for example the standardized Copenhagen approach (8) or the Duke bi-portal approach (9,10). The concept of minimally invasiveness was further with uniportal surgery (11). Within the chapter of single incision surgery there are two series of patients reported in 2016 which describe successful uniportal subxiphoid technique for anatomical lung resection in a total of 148 cases (12,13).

The use of subxiphoid port as a single incision demonstrated that from the subxiphoid region we obtain an acceptable angle in order to tackle all the hilar structures. The posterior mediastinum is still an area that is difficult to access including for the subcarinal lymphadenectomy. Another interesting and important feature of a subxiphoid port for lung surgery is the lack of innervation on the fibrous linea alba when compared to the intercostal spaces. The intercostal muscle and the neurovascular bundles are delimited by relatively fixed bony structures, the ribs, and the intercostal spaces are only 8 to 10 mm wide. The soft tissue of the subxiphoid region can spread easier than the intercostal space. This allow the delivery of large specimens avoiding the spread of the intercostal spaces which is a common cause of significant postoperative post-thoracoscopy pain.

The subxiphoid incision itself is not novel as it was firstly described in hand -assisted metastasectomy, by Mineo *et al.* (14), to gain access to both hemithoraces and

Figure 1 Subxiphoid port applied to robotic pulmonary lobectomies. Section I: this clip demonstrates the patient position, marking of the patient and the placement of the ports for a left sided procedure. Section II: the video shows a robotic right lower lobectomy, for early stage primary pulmonary malignancy, with the adoption of a subxiphoid port as the assistant port (15).
Available online: http://www.asvide.com/articles/1421

palpate the lungs but avoiding injury to the intercostal nerves.

Therefore, we adopted a subxiphoid port as a utility port during VATS procedures and this allowed us to reduce the intercostal incisions to 5 mm and developed this into a procedure called Microlobectomy (www.microlobectomy.com). We then applied this technique during robotic procedures and used a subxiphoid assistant port for robotic pulmonary lobectomies. The aim is to reduce the post-operative pain.

Surgical technique

We routinely mark the subcostal margins, the xiphisternum and the midline from the xiphisternum to the umbilicus (*Figure 1*, Section I) (15). This allows accurate marking before the patient is draped. The patient is positioned as usual in the lateral decubitus position but the midline is not covered. We use Cerfolio set up (2). The first port, a 5 mm port, is positioned over the ninth rib and 2 cm from the posterior midline. Further robotic arm ports are placed 12 cm and 22 cm from the spinous processes. A further anterior port is placed under vision as anteromedially as possible either in the same intercostal space or in the space above, and finally the subxiphoid port is performed, again under vision and with CO_2 insufflation. This replaces the assistant port. The robot is docked from the head and a Maryland bipolar forceps is used in arm 1, a Cadiere in port 2 and a 5 mm lung grasper for retraction is in arm 3. The bedside assistant hands swabs to the surgeon, uses suction and positions the staplers through the subxiphoid port. Also the lymph nodes are removed subxiphoid. As the port is inferior and anterior to the camera, this site is under vision and we do not need the bag for removal of lymph nodes. Once the lobe is completely resected this is placed into a bag and reduced in size (air and blood are drained by incising the vein and the stump of the bronchus). We now extend the incision of the subxiphoid port along the vertical, pre-marked, line and up to 4 or 5 centimeters. Then the specimen is finally delivered from the subxiphoid port as shown in the video (*Figure 1*, Section II).

Comments

Although we do not have enough data to state that there is less post-operative pain and therefore reduced postoperative morbidities, the patients who underwent this procedure had excellent outcome and enhanced recovery, and have all been discharged home within two to four days. We experienced that intraoperatively there was significantly fewer conflicts between the robotic instruments and the assistant instrumentation. The camera was able to keep the port under direct view and the operator could hand easily specimens and swabs to the assistant, who experienced less collision and impingement with the robotic arms and the diaphragm. From this site, he entered, positioned and fired the tristaplers on the hilar structures and lung parenchyma.

We suggest that removal of the specimen through the enlarged subxiphoid port can reduce the post-operative pain as this avoids the spread of the intercostal space. Even if there is some pain from the subxiphoid area we have found that this does not impair the ability to cough or breathe.

Finally, we have not yet experienced any diaphragmatic or incisional herniae with this incision when used for robotic surgery.

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Robotic lung cancer surgery: review of experience and costs

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Abstract: Use of robot-assisted techniques is growing fast in several surgical disciplines, now including thoracic surgery. The paper reviews experience of robotic surgery to resect lung cancer and in particular analyzes data on the costs of these procedures in comparison to open surgery and video-assisted thoracoscopic surgery (VATS). Retrospective studies published over 14 years show that robotic surgery for lung cancer has the advantages of minimally invasive surgery for patients, and some advantages over VATS for the surgeon. Limited data indicate that oncological outcomes are comparable with those of VATS and open surgery, while lymph node dissection may be more radical. Other studies indicate that robotic surgery for lung cancer offers no advantages either in terms of costs or outcomes. The high costs of purchase, maintenance and consumables are a concern and continue to limit uptake of robot systems in thoracic surgery. Most studies—but not all—indicate that robotic surgery for lung cancer is more expensive than VATS and open surgery. However limited data also indicate that hospitals can make a profit from robotic thoracic surgery, as costs seem to be lower than reimbursements from paying bodies. Nevertheless robotic thoracic surgery is still too expensive for many public hospitals, particularly in low income countries. Entry of new surgical robot manufacturers onto the market will bring much-needed competition that may also lead to cost reduction.

Keywords: Robotic thoracic surgery; costs; lung cancer; lung lobectomy; video-assisted thoracoscopic surgery (VATS); open surgery

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Introduction

Robot-assisted surgery for lung cancer was introduced in 2002 (1,2). After a slow start, use of a robot to perform lobectomy and other pulmonary excisions has increased rapidly from 2009. According to a study on non-academic hospitals in the United States, based on the database of the Agency for Health Care Research and Quality, in 2009, 66% of lobectomies were performed by thoracotomy, 33% by video-assisted thoracoscopic surgery (VATS), and only 1% by robot-assisted surgery, while by 2013, robotic resections had risen to 11% of the total (3). An analysis of the US Nationwide Inpatient Sample database (4) found a rapid increase in the number robotic lobectomies performed between 2008 and 2011, and also of the number of centers offering robotic lung surgery.

Several studies indicate that robotic surgery for lung resection is safe, and is associated with similar oncological outcomes to VATS and open surgery (5-8). Furthermore robot-assisted lung surgery offers several advantages to the surgeon summarized as improved vision and more precise and comfortable instrument manipulation (9,10).

Principal limitations to the wide adoption of robotic thoracic surgery are perceived as high capital and running costs of the robot instruments (11,12). Furthermore it would seem that use of robotic surgery in general has not improved patient outcomes as dramatically as the first wave of minimally invasive surgery did (13,14), so it is important to provide a balanced assessment the advantages and disadvantages of robot-assisted surgery for lung resection. In this article we make an attempt to do this, first by reviewing published experience of robotic surgery for lung cancer, then by evaluating data on the costs of robotic thoracic surgery in comparison to open and video-assisted approaches. Finally we assess prospects for cost reduction in the near future.

The da Vinci surgical system

At present the only manufacturer of robotic surgery equipment is Intuitive Surgical Inc. CA, USA. Intuitive's line of da Vinci Surgical robots is sold worldwide directly by the company or by agents such as AB Medica, SpA (in Italy). Intuitive Surgical aimed to establish da Vinci surgical systems as standard for complex surgical procedures in four main areas: urology, gynecology, cardiothoracic surgery and general surgery. Part of its approach consists of recruiting leading surgeons in these areas and encouraging them to communicate their experience with robotic techniques to their peers to thereby introduce surgeons, hospitals and patients to the advantages of minimally-invasive surgery performed robotically. It is also evident however that there is widespread direct-to-consumer advertising, and patients are increasingly requesting robotic surgery, with little knowledge of whether it is indicated for their particular condition (14).

Although some centers enjoy discounts, a new da Vinci robotic system generally costs around 2 million US$ ranging from 1$ to 2.5$ million for each unit (15). Maintenance costs are around 10% of the initial capital outlay per year (15). The cost of "consumables" which includes the instruments attached to the robotic arms is also high, mainly because the instruments can be sterilized and reused only a limited number of times, as specified by the company, irrespective of their duration of use in a given operation. Finally, depreciation costs are also significant.

The costs of training the surgeon and the surgical team also need to be considered. Several authorities (16-19) consider that the trainee surgeon should first gain familiarity on a simulator and then progress to a dual console so as to gain proficiency at switching the arms, using the endowrist instruments and suturing. A simulator costs 35,000–158,000 US$ (20) and is typically sold with the machine, as with the latest XI system robots. A second console increases the cost to around 3 million US$ (21) but makes it possible for the trainee to be tutored in real time by an expert robotic surgeon. Some hospitals purchase a da Vinci robot as a strategic choice unrelated to current cost, with the aim of stimulating clinical research, increasing publications, and enhancing their attractiveness to both patients and young surgeons. The purchase often follows an evaluation of the advantages and disadvantages of the robot system, but costs may be a non-critical aspect of this evaluation (22).

In Italy, as in most European countries, hospitals are reimbursed for admissions, treatments and surgical procedures by the Italian Health Service at fixed rates determined by a modified DRG system. Additional remuneration is not provided for robotic procedures except for robotic prostatectomies.

Literature review on robotic surgery for lung cancer

Following initial experience (1,2) Park *et al.* (23) reported on 34 patients undergoing robotic lobectomies with two thoracoscopic ports and a 4-cm utility incision. Conversion was performed in 4/34 (12%) patients, and all received an R0 resection. Operative mortality was 0%, median length of stay was 4.5 days (range, 2–14 days) with median operating time 218 minutes (range, 155–350 minutes). The authors concluded that robot assistance for video-assisted thoracic surgical lobectomy was feasible and safe. Veronesi *et al.* reported on the feasibility and safety of four-arm robotic lung lobectomy in 2009 (7). Fifty-four lung cancer patients treated by robotic lung lobectomy were compared with 54 patients who received open surgery. These experiences indicated that robotic lobectomy with lymph node dissection was practicable, safe, and associated with shorter postoperative stay than open surgery with similar number of lymph nodes removed. In 2012 a multi-institution group (24) presented technical aspects and initial results of robotic anatomic segmentectomies using the four-arm technique described by Veronesi *et al.* (7). Outcomes were comparable with those obtained by open surgery and VATS; however the authors noted that precise radical dissection of mediastinal and hilar lymph nodes was easier by the robotic approach than with VATS.

In 2011, Dylewski *et al.* (25) reported on 200 robotic lung resections performed using their approach involving chest cavity insufflation with CO2. Perioperative results were good with mean postoperative stay of 3 days, mean duration of surgery 90 minutes, 2% 60-day mortality and 26% morbidity. Also in in 2011, Cerfolio *et al.* (26) published their experience on a consecutive series of 107 four-arm robotic lobectomies, in comparison to 318 lobectomies performed by open surgery. The robotic group had better quality of life, shorter hospital stay, and lower mortality and morbidity than the thoracotomy group. In 2012 Louie *et al.* (3) published a case-control analysis of consecutive anatomic lung resections performed by robotic surgery or VATS. Surgical and postoperative outcomes were similar in both groups, but patients who received robotic surgery had significantly shorter duration of narcotic use and earlier return to normal activities than patients who received VATS.

Data on oncological outcomes with robotic surgery are limited. A multi-institute retrospective evaluation of over 300 robotic lobectomies (8), performed on mainly stage I patients with non-small cell lung cancer, indicated long-term stage-specific survival that was acceptable and consistent with prior results for VATS and thoracotomy.

Rate of nodal upstaging has been used a surrogate for completeness of nodal evaluation and quality of surgery. In one study (27) it was found that rate of nodal upstaging for robotic resection was greater than for VATS and similar to that for thoracotomy, however the authors noted that a larger series of matched open, VATS and robotic patients was necessary to confirm their finding. In comparative studies by Veronesi *et al.* (7) and Cerfolio *et al.* (26) the median numbers of lymph nodes removed by robotic and open procedures were closely similar, suggesting that robotic resection achieves similar oncological radicality to that achieved by thoracotomy. In their 2016 study, Louie *et al.* compared outcomes between robotic surgery and VATS in non-small cell lung cancer cases archived in the US Society of Thoracic Surgeons database. The found that, while operating times were significantly longer in robotic cases, all postoperative outcomes were similar, including complications, 30-day mortality, and nodal upstaging, indicating substantial equivalence between robotic surgery and VATS (3).

Notwithstanding these encouraging findings more long-term comparisons of outcomes in lung cancer patients treated by robotic and VATS approaches are required.

Costs of robotic surgery for lung cancer

The main argument against robotic thoracic surgery is greater costs in comparison to VATS. Several papers have analyzed costs, but results have been conflicting. Park *et al.* (28) analyzed lobectomies performed in 267 cases by open surgery, 87 cases by VATS, and by cases 12 by robot-assisted procedure. They found that operating times were similar for each group, and length of postoperative stay was shorter for VATS and robotic surgery (4 days) compared to open surgery (6 days). However robotic surgery cost US$ 3,981 more than VATS per operation, mainly due to the costs of robotic disposables and drapes. Importantly, however, robotic surgery was estimated to cost US$ 3,988 less than open surgery. This analysis did not consider depreciation of the robot instrument but did cite a theoretical cost analysis, which, assuming a 7-year life-span of the robot and 300 operations per year, estimated an additional cost of US$ 857 per robotic patient. When this depreciation cost was added to the original estimate of Park *et al.* (28) robotic surgery was still cheaper than open surgery.

One of the largest single-surgeon experiences in robot-assisted surgery was reported in 2014 by Nasir *et al.* (9). Although these authors found that robot-assisted lobectomy for cancer offered outstanding results, excellent lymph-node removal and minimal morbidity and pain, costs were higher than for VATS.

Median total costs were US$ 15,440 per patient against a median Medicare reimbursement of US$ 18,937, so notwithstanding the higher cost, robotic surgery was profitable for the hospital.

A retrospective analysis by Dylewski *et al.* (29) of 176 robot-assisted lobectomies compared to 76 VATS lobectomies, found that the robot assisted approach was US$ 560 per case lower than VATS, with most of the cost-saving due to reduced length of hospital stay and lower overall nursing costs.

However other papers, particularly large database comparisons, indicate considerably greater costs for robotic thoracic surgery. An analysis by Swanson *et al.* (30) on 15,502 operations (96% VATS, 4% robotic) found that robot-assisted thoracic surgery was associated with higher hospital costs, longer operating times, and no improvement in adverse events. Considering only lobectomies in a matched-pair analysis, robotic surgery was about 15% more expensive than VATS (US$ 21,833 *vs.* US$ 18,080). The robot-assisted procedures were performed in 40 different hospitals, equating to <8 cases/center over the two-year study period. Thus most hospitals were performing too few robotic procedures to complete learning or to maintain proficiency. However this is likely to have has only a limited effect on costs (perhaps by increasing operating times or complications compared to operations performed by experienced surgeons).

Paul *et al.* (4) compared perioperative outcomes and costs for robot-assisted lobectomy with thoracoscopic lobectomy from 2008 and 2011 (2,478 robotic pulmonary lobectomies and 37,595 VATS lobectomies), finding that robot-assisted surgery had higher costs and more complications. The results of this study may also have been biased because a greater proportion of robot-assisted operations were performed in small-to-medium sized hospitals, in non-teaching hospitals, and those with moderate patient volume, explaining the greater proportion of complications and possibly also part of the increased costs.

Deen *et al.* (31) analyzed 184 consecutive patients with similar comorbidities who underwent lobectomy or segmentectomy (69 by thoracotomy, 57 by robot, and 58 by VATS). There were no differences in complication rate or length of hospital stay, but significantly different operation times. Furthermore overall costs, which included depreciation, differed significantly between the groups: VATS was the least expensive, and robotic surgery was the most expensive procedure. There were no significant differences in overall cost between thoracotomy and robotic surgery, but robotic surgery cost US$ 3,182 more than VATS ($P<0.001$) attributed to the cost of robot supplies and depreciation. The authors commented that operating times and robot consumables needed to reduce in order for robotic surgery to become competitive.

It is noteworthy that no cost analyses of robotic thoracic surgery have yet been published by European hospitals or surgeons. An analysis of conducted at our own hospital in Italy (submitted for publication) indicates that costs for robot-assisted surgery (lobectomy or segmentectomy for clinical stage I or II NSCLC) were higher than for both VATS and open surgery, but all operations are profitable since reimbursement from the Italian Health Service exceeded costs. Notably, robot-assisted surgery was associated with reduced duration of stay (both in hospital and in the intensive care unit), reduced postoperative examinations, and reduced use of painkillers and other drugs.

The two main robotic techniques for lung lobectomy may differ intrinsically in costs, but this has not been verified by comparative cost analyses. Dylewski *et al.* (25) use four accesses, but only three robotic arms thus sparing the cost of one instrument compared to the four accesses of Cerfolio *et al.* (26). The recent paper by Tchouta *et al.* (32) showed that those robotic lung lobectomies performed in high volume centers were associated with significantly shorter hospital stay and significantly lower mortality. It is reasonable that high volume can also contribute to cost reduction by standardization of patient preparation, robot docking and surgical procedures (9,17) as well as by reducing operating times, hospital stay and complications.

Robotic thoracic surgery—the future

The lack of randomized studies comparing outcomes in with those achieved by VATS or open surgery is a major concern. A recent randomized trial (33) showed that pain is reduced and quality of life is better in patients given VATS compared to open thoracotomy for early stage lung cancer. Similar data are sorely needed for robotic thoracic surgery. Our institute (Humanitas Research Hospital) has started a multicentred randomized trial (NCT02804893) comparing robotic surgery with VATS in lung cancer patients scheduled for lobectomy or sublobar resections. Three hundred patients will be recruited, and complications, conversions to open surgery, lymph node dissection, and quality of life will be assessed.

The future development robotic surgery in general is likely to be enhanced by the arrival of new surgical robots from new manufacturers. Medtronic and Johnson and Johnson (34) are developing surgical robots which will challenge Intuitive Surgical monopoly and hopefully drive costs down. Notwithstanding these problems we expect that use of robot-assisted surgery to perform thoracic surgery in general, and lung cancer resections in particular, will continue to increase.

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Footnote

Conflicts of Interest: G Veronesi is a consultant for ABI Medica SpA and Medtronic. And other authors have no conflicts of interest to declare.

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Pulmonary Surgery

Continuous 389 cases of Da Vinci robot-assisted thoracoscopic lobectomy in treatment of non-small cell lung cancer: experience in Shanghai Chest Hospital

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Background: To analyze the perioperative indexes of 389 patients with non-small cell lung cancer in single center after robot-assisted thoracoscopic (RATS) lobectomy, and to summarize the surgical key points in robotic lobectomy.

Methods: The clinical data of 389 stage I non-small cell lung cancer patients who underwent RATS lobectomy from May 2013 to December 2016 were retrospectively analyzed. Among them, there were 261 females (67.1%) and 128 males (32.9%); aged from 20–76 years old, with a mean age of 55.01 years; with ASA I in 106 cases, ASA II in 267 cases and ASA III in 16 cases; with BMI from 16.87–34.05, averaged at 23.09±2.79. The largest tumor in preoperative chest CT measurement was 0.3–3.0 cm, ranging from 1.29±0.59 cm; with stage Ia in 153 cases, stage Ib in 148 cases, stage Ic in 32 cases, stage IIb in 26 cases and stage IIIa in 30 cases; including 380 adenocarcinomas and 9 squamous carcinomas.

Results: The operating time was 46–300 min, averaged at 91.51±30.80 min; with a blood loss of 0–100 mL in 371 cases (95.80%), 101–400 mL in 12 cases (3.60%) and >400 mL in 2 cases (0.60%); there were 4 (1.2%) conversions to thoracotomy, in which 2 patients had massive hemorrhage and 2 patients had extensive dense adhesion; there was no mortality during operation and perioperatively. The drainage on the first day after operation was 0–960 mL, averaged at 231.39±141.87 mL; the postoperative chest tube was placed for 2–12 d, averaged at 3.96±1.52 d; the postoperative hospital stay was 2–12 d, averaged at 4.96±1.51 d, with postoperative hospital stay >7 d in 12 cases (3.60%). The postoperative air leakage was the main reason (35 cases, 9%) for prolonged hospital stay, and there was no re-admitted case within 30 days. All the patients underwent systemic lymph node dissection. The total cost of hospitalization was 60,389.66–134,401.65 CNY, averaged at 93,809.23±13,371.26 CNY.

Conclusions: The application of Da Vinci robot surgery system in resectable non-small cell lung cancer is safe and effective, and could make up for the deficiencies of traditional thoracoscopic surgery. The number and level of robot surgery in our center have reached international advanced level, but the relatively expensive cost has become a major limitation in limiting its widespread use. With continuous improvements in robotic technology, its scope of application will be wider, which will inevitably bring new insights in lung surgical technology.

Keywords: Da Vinci robot surgery system; lobectomy; minimally invasive surgery

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Introduction

Following the widespread use of robotic-assisted surgical technology in urology, obstetrics and gynecology, and cardiac surgery, it has been widely used in thoracic tumor (1-4). Before the appearance of thoracoscope minimally invasive surgery, thoracotomy was the main approach that requires distraction of ribs (5-8). Compared with traditional open surgery, video-assisted thoracic surgery (VATS) is less invasive as it avoids damage to the structure of chest wall and distraction of ribs. VATS has less postoperative pain, shorter postoperative drainage and the hospital stay was shorter (5-12). Robotic surgery offers better maneuverability, accuracy, and stability over VATS, and provides high-definition, three-dimensional images for the surgeon. The innovative internal rotation wrist system and freely movable microsurgery enable microscopic surgical instruments to completely reproduce the human hand movements so as to achieve the coordination of hands and eyes. The system design can eliminate the adverse effect of surgeon's hand trembling on surgery. Its greatest innovation is to make remote operation possible. Robotic surgical system has been used in thoracic surgery such as mediastinal tumor resection, esophageal tumor resection, and lung tumor resection.

This article retrospectively analyzed 389 patients receiving robotic-assisted thoracoscopic lobectomy from May 2013 to December 2016 in Shanghai Chest Hospital. The operation time, intraoperative blood loss, postoperative drainage within 3 days, postoperative extubation days, postoperative hospital stay, total cost of operation were analyzed. This study was approved by the ethics board of Shanghai Chest Hospital [KS(P)1811].

Methods

Da Vinci surgical system

Da Vinci surgical system is an advanced robotic platform that is engineered to perform complex surgeries with minimal invasiveness. Da Vinci surgical system consists of three parts: surgeon's console, bedside robotic arm system and the imaging system. The surgeon sits in the console outside the sterile area of the operating room, and uses both hands (by operating two main controls) and feet (via foot pedal) to control the instrument and a three-dimensional high-definition endoscope. The bedside arm system is the operating part of surgical robot with primary function in providing support for the mechanical arm and camera arm. The assistant doctor works beside the bedside arm system in the sterile area and is responsible for changing the instrument and the endoscope to assist the surgeon in completing the operation. In order to ensure patient safety, the assistant doctor has higher priority over the motion of the bedside arm system than the chief surgeon. The imaging system incorporates with core processor and image processing instrument of the surgical robot, and is located outside the sterile area during the operation. It can be operated by circulating nurse and can be used for placing various types of assistive surgery devices. The surgical robotic endoscope has high-resolution three-dimensional (3D) lens, with more than 10 times of magnification in surgical field. It provides three-dimensional high-definition image in the body cavity of the patient for the surgeon, so that the surgeon can better handle the operating distance than conventional thoracoscopic surgery, with more recognition of anatomical structure and improved accuracy.

Patient data

There were 261 (67.1%) females and 128 males (32.9%); aged from 20–76 years, with a mean age of 55.01 years; with ASA I in 106 cases, ASA II in 267 cases and ASA III in 16 cases; with BMI from 16.87–34.05, averaged at 23.09±2.79. The diameter in chest CT was 0.3–3.0 cm, averaged at 1.29±0.59 cm; with stage Ia in 153 cases, stage Ib in 148 cases, stage Ic in 32 cases, stage IIb in 26 cases and stage IIIa in 30 cases; with left upper lobe in 37 cases, left lower lobe in 101 cases, right upper lobe in 105 cases, right middle lobe in 32 cases and right lower lobe in 114 cases; including 380 cases of adenocarcinoma and 9 cases of squamous carcinoma (*Table 1*). Preoperative examinations showed no external invasion, metastasis and tolerable cardiopulmonary function. The surgical approach was decided according to the surgeon's judgement and the patient's own economic condition. All the 389 patients completed the surgery successfully with no conversion.

Anesthesia, posture and incision option

All the patients in this group were treated with double-lumen endotracheal intubation, general anesthesia, intraoperative single-lung ventilation and contralateral decubitus position, with patient's upper extremities in flexion and holding pillow. The operating bed was adjusted to turn the torso into slight upward-folding position to widen the intercostal space passively. Da Vinci surgery completes lobectomy and systemic lymph node dissection

Table 1 Clinical materials of 389 patients

Clinical materials	Data
Gender, n (%)	
Male	128 (32.9)
Female	261 (67.1)
Age, years ($\bar{x}$ ± s)	55.01±10.46
Tumor site	
Upper lobe of right lung	105
Middle lobe of right lung	32
Lower lobe of right lung	114
Upper lobe of left lung	37
Lower lobe of left lung	101
Pathological type	
Adenocarcinoma	380
Squamous carcinoma	9
Pathological staging	
Ia	153
Ib	148
Ic	32
IIb	26
IIIa	30
ASA scoring	
Grade I	106
Grade II	267
Grade III	16

through the arms and auxiliary port. Position of ports: the camera port was generally in the axillary midline at 7th intercostal space. The left and right arms should be located in the same horizontal plane as the camera port, and the distance between the arms should be around 8 to 10 cm to facilitate overall motion and to reduce the direct collision of arms that would interfere with smooth surgery. The auxiliary port is preferred in the 3th or 4th intercostal space at anterior axillary line.

Surgical procedures

The camera is inserted through trocar at targeted position. After examining the thoracic cavity for no extensive adhesion, carbon dioxide is inflated to ensure clear vision and to accelerate residual gas discharging in lungs. Then two arms are placed, and the bedside arm system is docked. Generally, the right arm carries cautery hook, and the left arm carries Cadiere forceps. For the lower lobe resection with well-developed lobar fissure, the assistant lifted upper lobe vertically, then exposing artery and dissecting the 11th lymph node station. After handling the lobar fissure, the next step is to pull the lobe anteriorly to expose postmediastinum, then dissecting the 7th lymph node station and separating the lower lobar bronchi; and then the lower lobe is pulled vertically to expose and free anterior pulmonary hilus. The lower lobe is then pulled in a cephalad direction to expose and to manage the lower pulmonary ligament. The 2nd and 4th lymph node stations are dissected at the end of operation (5th and 6th stations in the left) (1).

Results

The mean operation time (from skin incise on and installing to the end of sternal closure) for robotic lobectomy was 91.51±30.80 min, ranging between 46–300 min, with estimated intraoperative blood loss of 0–100 mL in 371 cases (95.80%), 101–400 mL in 12 cases (3.60%) and >400 mL in 2 cases (0.60%); there were 4 conversions (1.2%) in which 2 cases had massive hemorrhage due to pulmonary artery branches and 2 cases had difficulty in separating due to extensive dense adhesions; there was no mortality during surgery or within 30 days after surgery.

On the first after surgery, the mean drainage was 231.39±141.87 mL; the drainage duration ranged between 2–12 d, and no patient left the hospital with chest tube; the postoperative hospital stay was 2–12 days, averaged at 4.96±1.51 days, with postoperative hospital stay >7 days in 12 cases (3.60%). The postoperative air leakage (35 cases, 9%) was the main reason for prolonged hospitalization, and there was no re-admitted case within 30 days.

All the patients underwent lymph node sampling or lymph node dissection, with lymph nodes taken in 2–9 sets, averaged at 5.69±1.46 sets, and the number of lymph nodes taken in 3–21, averaged at 9.80±3.43.

The total cost of hospitalization (including self-paying and health-care coverage) was 60,389.66–134,401.65 CNY, averaged at 93,809.23±13,371.26 CNY.

Discussion

Several studies on robotic lobectomy for lung cancer occurred from 2002 to 2010 (9-19). Melfi *et al.* (9) reported 107 cases of robot-assisted lobectomy, which performed systematic lymph node dissection. Previous literature showed that the results of robotic surgery were satisfactory both in terms of the incidence of complications and in terms of various statistical indicators in intraoperative and perioperative periods. The feasibility and safety of this new technique was demonstrated early in the 34 cases of robot-assisted lobectomy reported by Giulianotti *et al.* (10) in 2003, and the 38 cases of robot-assisted lobectomy reported by Park *et al.* (11) in 2006. Gharagozloo *et al.* (12) reported 100 cases of robot-common thoracoscopic hybrid lung cancer surgery, in which the robot-common thoracoscopic hybrid surgery was conducted in two steps. The robot was used in freeing blood vessels and pulmonary hilus and mediastinal lymph node dissection, the remaining part was excised by common thoracoscopy to complete lobectomy. In this report, the incidence of postoperative complications was as high as 21%, and 3 cases died in perioperative period. They analyzed that the reason may be there were a large number of high-risk patients. The mortality of the last 80 cases was significantly reduced, so the first 20 cases can be considered as the learning stage. They thought that robots had obvious advantages in dissecting mediastinal lymph nodes, pulmonary hilus and pulmonary vessels. Veronesi *et al.* (13) first reported comparative study on chest-opening (MUSCLE-SPARING incision) lobectomy with four-armed robotic lobectomy. The postoperative hospital stay in the robot group was shorter, but the operation time was longer than the chest-opening group. However, with the end of the learning period, the operation time was significantly shortened. The experience in our center showed that Da Vinci robot-assisted lobectomy offered advantages over conventional thoracoscopic surgery, mainly in 3D field of view and the unique internal wrist rotation system, which provided surgeon with more comfortable and smoother operating experience; meanwhile, the sub-damage to the surrounding tissue was less, the trauma was smaller, and recovery was faster. The patients may have less postoperative pain after robotic surgery, but this still required further prospective experiment for confirmation.

Whitson *et al.* (20) systematically reviewed and compared the short-term incidence of complications and long-term survival rate of thoracoscopic lobectomy and chest-opening lobectomy in treatment of early-stage NSCLC. Thoracoscopic lobectomy was thought to provide patients with significant survival benefits. The article also showed that minimally invasive surgery had less immunosuppression in patients, while the immunosuppression caused by thoracotomy may stimulate tumor growth. Only Park *et al.* (11) had so far reported the long-term survival of robotic lobectomy. The study followed up 325 patients undergoing robotic lobectomy in treatment of early NSCLC from 2002 and 2010, with 76% of stage I lung cancer, 18% of stage II and 6% of stage III. The median follow-up period was 27 months, and the 5-year survival rate was 80%. These limited follow-up data indicated that the survival rate of robotic lobectomy was acceptable. The 389 cases of robot-assisted thoracoscopic (RATS) lobectomy performed at our center had no recurrence in follow-up so far, which may be due to shorter follow-up period, but long-term data was still required.

There are several different approaches to robotic lung resection that have been reported so far. Park *et al.* used thoracoscopic technique in robotic surgery, including perforating location and anterior-to-posterior hilar approach through two thoracoscopic holes with three mechanical arms and a 4 cm-long auxiliary incision for assistance. There are also some reports on the use of hybrid “4-hole method”, that is technical means with three mechanical arm holes and an auxiliary hole. Dilewsky and Cerfolio reported on the “full-hole” robotic lung resection technique using four mechanical arms. In order to maintain the intra-thoracic pressure of carbon dioxide, only one incision was made to remove specimens at the end of the procedure. Qingquan Luo Surgery Group in Lung Tumor Clinical Medical Center in Shanghai Chest Hospital began exploring robotic lung resection surgery from 2009, starting with full-hole and the use of ultrasonic knife for free operation. The biggest disadvantage of the surgical procedure was that suction apparatus could not be used to suck the exposure. Once the suction apparatus was in, all the pulmonary lobes would be opened due to negative pressure, leaving no surgical space. Therefore, during the operation procedure, the free operation should be carefully operated. Once bleeding occurred, the operation field of vision would be very unclear, needing the stuffing with gauze to stop bleeding by compression, affecting the operation flow and extending the operation time. Another disadvantage was that many elderly patients could not tolerate “artificial pneumothorax”. The injected carbon dioxide to maintain certain pressure would affect the patient’s hemodynamics, reducing blood pressure and slowing down heart rate. Based on above preliminary exploration, we changed the surgical technique to a hybrid “4-hole method” and changed the operating instrument to electrical hook. Since the auxiliary holes can extend into

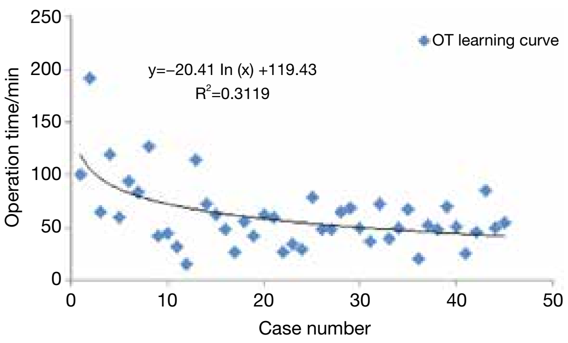

Figure 1 Learning curve of da Vinci robot-assisted lobectomy for the first 50 cases.

common surgical instruments such as oval pliers and suction apparatus to pull lung lobes and expose field of vision, greatly simplifying the operation procedure. The fastest surgery time of lobectomy was 7 minutes. Currently, the average surgery time of lobectomy was about 45 minutes. Plus, lymph node dissection, the surgical process was controlled in 60 minutes. There has been no difference with conventional thoracoscopic surgery in surgery time.

Currently, the complete degree of lymph node dissection is a predictive factor of local recurrence. Veronesi *et al.* (13) and Cerfolio *et al.* (21) reported of no statistical difference in the number and set of lymph node dissection between robotic surgery and thoracotomy. The local recurrence rate was similar to that of thoracotomy, without significant difference. The local recurrence control was the same as the thoracotomy. These two studies also compared the thoracoscopic surgery and robotic surgery in the extent of lymph node dissection, finding no significant difference. There was no significant difference in the control of local recurrence rate. The experience in our center showed that Da Vinci robotic surgery system could perform en bloc resection of lymph nodes and their surrounding fat due to the rotating electrocoagulation hook. With clear field of view, inner rotating wrist system and operating system that filtered hand trembling, its dissection degree was higher than traditional thoracotomy. However, current comparisons on robotic, endoscopic and open surgeries were all retrospective studies. The thoroughness and safety of robotic surgical system and long-term prognosis of patients still needed prospective randomized and controlled clinical trials for confirmation.

In the 389 cases of lobectomy, we completed two cases of bronchial sleeve resection and one case of pulmonary bronchial double-sleeve resection. The flexible arm of the robot made the entire anastomosis process very smooth, and the average time for bronchial anastomosis was 15 minutes. Our advice and next step is to take full advantage of Da Vinci's meticulous operational advantages to expand the minimally invasive thoracic surgery to previously not involved lung cancer treatment area, such as sleeve resection and angioplasty, to demonstrate its irreplaceable value factors.

There is evidence showing that robotic surgery has shorter learning curve than laparoscopic surgery. Chang *et al.* (22) reported that after 8–10 hours of robotic surgery training, robot operation was basically achievable. After 14 hours of training, the operating time was significantly shortened. Hernandez *et al.* (23) divided the surgeons into two groups according to laparoscopic surgery experience, asked them to use robot for small intestine dissection and found that there was significant difference between first and fifth small intestine dissection time. The fifth operation time was significantly shortened. Surgeons were soon proficient in robotic surgery system, which was unrelated with the surgeons' previous laparoscopic surgery experience.

Melfi and Mussi (17) did not provide a learning curve in their report of 107 cases of robotic lobectomy, but they suggested that a minimum of 20 cases of surgical experience was needed for surgeons and surgical nurses to be adept. They also highlighted the need to standardize various steps. Based on the length of hospital stay for surgery, Gharagozloo *et al.* (12) also suggested that 20 surgeries were needed to obtain adequate surgical skills. Veronesi *et al.* (13) reported 91 cases of robotic lobectomy, in which the median surgery time and postoperative hospital stay for the first 18 patients were longer, with statistical significance, but the incidence of complications was not significantly different. The experience in our center also showed that the first 20 cases were in the learning stage, and the surgery time for the latter 20 cases was significantly shorter (*Figure 1*). The learning curve showed that during the initial exploring phase, the surgery time was about 120 minutes. With the accumulation of experience after about 20 surgeries, the surgeon can basically master the robotic surgery system. At present, there is no significant difference between robotic lobectomy and conventional thoracoscopic surgery in surgery time.

The study reported by Jane *et al.* (24) in 2011 retrospectively compared the advantages and disadvantages of robotic lobectomy and general thoracoscopic lobectomy. Their results showed that the intraoperative blood loss in the robot group was less (219 *vs.* 374 mL, P=0.017), and the median hospital stay was shorter (6 *vs.* 9, P<0.001). Their data showed that the learning curve of robotic lobectomy was shorter than that of general thoracoscopic lobectomy.

At present, the biggest problem in robotic surgery is its high surgical costs, which include the cost of robotic surgery system and the cost of disposable consumables, and this has greatly hampered the development of robotic surgery in China. In 2008, Park and Flores (25) reported that Da Vinci robotic surgery system needed one million dollars, annual maintenance cost was 100,000 dollars, and each operation was short of 730 dollars. They generally estimated that it was about 3,981 dollars more expensive than conventional thoracoscopic surgery. In developing countries like China, there are very few patients who can afford such high costs of surgery. However, as people's income increases, the coverage of medical insurance increases, and the reimbursement ratio increases, the costs of surgery can already be accepted by most patients. At present, our center is also trying to reduce the use of disposable consumables and make full use of the robot's unique advantages in operation, which can also greatly reduce the operation costs. China has begun to independently develop medical surgical robotic system, which I believe will challenge the current market price of robotic surgery system in the near future.

Most of the existing literature shows that robotic surgical system is safe and feasible for thoracic surgery, and the perioperative effect is similar to that of traditional video-assisted thoracoscopic surgery. However, as current development time of the surgery is still short with limited experience, the device and usage costs, necessary training of surgeons and operating room personnel, device setting time, and limited mechanical arm devices are all issues that need to be addressed. And current robot system lacks of fine force feedback, and lacks of information on mid-and-long-term prognosis. Nonetheless, more prospective randomized and controlled trials are expected in the future to prove that Da Vinci robot surgical system can improve surgical complications, pain, hospital stay and operation time, and also achieve the same mid- and long-term effects as other surgical procedures.

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Footnote

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Pulmonary Surgery

Robotic lobectomies: when and why?

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Abstract: During the last decade, an abundance of papers has supported minimally invasive pulmonary resections (MIPR) *vs.* traditional open approach. Both video assisted thoracic surgery (VATS) and robotic thoracic surgery have shown better perioperative outcomes and equivalent oncologic results compared with thoracotomy, confirming the effectiveness of the MIPR. Despite the profound changes and improvements that have taken place throughout the years and the increasing use of robotic system worldwide, the controversy about the application of robotic surgery for lung resections is still open. Some authors wonder about the advantages of using a more expensive and more complex platform for thoracic surgery instead of the more established VATS technique. Robotic thoracic surgery represents, although the cumulative experience worldwide is still limited and evolving, a significant evolution over VATS, nonetheless several authors criticize the longer operative time and the high costs of robotic procedures. The aim of this paper is to answer two relevant questions: why and when the application of robotic technology in thoracic surgery is appropriate?

Keywords: Minimally invasive; robotic; lung cancer; lobectomy

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According to NCCN guidelines (version 5.2017) regarding non-small cell lung cancer (NSCLC) "*VATS or minimally invasive surgery (including robotic-assisted approaches) should be strongly considered for patients with no anatomic or surgical contraindications, as long as there is no compromise of standard oncologic and dissection principles of thoracic surgery*" (1).

Throughout the course of the last decade, the role of minimally invasive surgery in thoracic surgery has been increasing. Since 1992 when Lewis *et al.* (2) firstly reported the use of video-assisted surgery to perform lobectomies, many changes have occurred to the thoracic approach to make surgery less invasive. Although the clear benefits versus open approach (less trauma, pain, and shorter hospital stay), video assisted thoracic surgery (VATS) has some limitations for the surgeon: bidimensional vision, camera under assistant's control, long instruments in fixed ports, which create a fulcrum effect, and lack of tactile feedback.

Robot technology is an evolution of VATS, developed to overcome the restrictions of manual videothoracoscopy, maintaining the advantages related to low invasiveness.

The robotic system consists of a master console used by the surgeon to manipulate the patient cart, connected via electrical cables and optic fibres with three instrumental arms and a camera arm. The surgeon's movements are transmitted to the cart manipulating master handles with a highly sensitive sensor able to filter physiologic hands tremor (6-Hz motion filter). The 3D high definition camera gives to the surgeon a much-improved vision compered to VATS and open approach. The robotic instruments, thanks to the seven degrees of freedom, allow the replication of the human wrist movement into the chest cavity. The three degrees of movement (pitch, yaw and insertion) are given by the cart arm; four degrees (internal pitch, internal yaw, rotation and grip) are guaranteed by the tip of the instrument, called in fact EndoWrist (3).

The da Vinci system® (Sunnyvale, CA, USA) is currently

Figure 1 Xi surgical cart positioning: laser crossair.

Figure 2 Patient position.

considered the only complete surgical system to perform thoracic surgery (4). During the years, four different generations of the robotic system have been developed (Standard, S, Si and Xi) with several improvements of the technological features, allowing feasible and safe surgical procedures.

The last platform, Da Vinci Xi, is an important evolution of the previous systems. Significant improvements are centered on the patient cart features and on the docking process. The patient cart is a mobile platform with a boom-mounted system, easier to move than the prior systems. On the boom, there is a laser crosshair facilitating the alignment of the patient cart with the camera port (*Figure 1*). The patient cart can be placed in any position around the patient. The camera is smaller than the one in the previous systems and fits into an 8 mm trocar, which allows a port-to-port change of position. The Xi platform has also a laser targeting system, which assists with the alignment of the cart to target anatomy and to limit the arms collisions, frequent in the previous systems. All Xi instruments have longer shafts and the distance between robotic arms can be less than in the Si (6 *vs.* 8 cm). The robotic arms have an additional joint (patient clearance) which allows rotating away and avoids the collision with the patient's body or with the other arms. Da Vinci Xi is provided with robotic staplers that allows performing a totally robotic lung resection without external positioning stapler under bidimensional vision and which avoids traumatisms during the manual staplers insertion through intercostal space.

Why?

Despite the profound changes and improvements that have taken place during the years and the increasing use of robotic system worldwide, the controversy about the application of RATS for lung resection is still open.

A drawback reported by most surgeons is the longer operating times: the robotic time to perform a lobectomy is averagely longer than that of an open or a VATS approach.

The average times reported by more experienced robotic surgeon are between 100 and 228 min (5-12). Anyway, the introduction of the Xi system has sensibly decreased the mean operative time of robotic procedures, thanks to shorter docking time and to technological improvements of the platform.

In our opinion, an important mean to decrease surgical time is the standardization of the surgical technique, firstly the port mapping: a mistake during this point could complicate the identification and the proper isolation of hilar structures with a longer operative time. Different authors describe several techniques in regard. Park *et al.* (13) described a three robotic arms technique with two thoracoscopic ports and a 4 cm utility incision. Gharagozloo *et al.* (6) reported a hybrid technique with three robotic arms, (positioned at the 8th, camera, 6th and 5th intercostal space), in this case the surgeon used a robotic approach for hilar structures dissection, then the platform was removed and he returned to the operating table to complete the operation. Louie *et al.* (11) and Anderson *et al.* (14) described a three-arm robotic lobectomy with a utility port; Jang *et al.* (15) used a utility incision at the fifth intercostal space. Ninan and Dylewski (16) reported a three arms technique using the same intercostal space for all ports (the 5th or 6th) and a utility port over the 11th rib. Veronesi *et al.* (7) and Cerfolio *et al.* (10) described four arms robotic lobectomy without utility incision.

At the Robotic Surgery Unit in Pisa we are currently using a four arms technique without utility incision. The patient is positioned in lateral decubitus, as for a posterior-lateral thoracotomy, with the operating table tilted at the tip of the scapula (*Figure 2*). When using Si platform the camera port (10 mm) is positioned in the 7th or 8th intercostal space

Figure 3 Xi port-mapping.

on the mid axillary line; the other ports (8 mm) are positioned in the 5th or 6th intercostal space on the anterior axillary line, in the 6th or 7th intercostal space on the posterior axillary line and in the auscultatory area. Recently, thanks to the introduction of the robotic staplers in the Xi platform, we have modified our port mapping. The posterior ports are positioned (when possible, depending on the chest dimension) along the same intercostal space (7–8th intercostal space) and in the auscultatory area (between the posterior rime of the scapula and the spine). The anterior port is positioned in the 5–6th intercostal space on the anterior axillary line, just over the diaphragm (*Figure 3*). Considering the variability of the chest dimensions, however, it is highly recommended to check the position of the port through the internal camera view, in order to perform the higher posterior access at the level of posterior inter-lobar fissure line. The Xi port mapping modification simplifies the stapler movements and allowing the positioning of all the posterior access in the same intercostal space, reducing postoperative pain. Thanks to our long experience with all the generations of robotic platforms, we have had the possibility to optimize the trocar position standardizing the procedure.

Currently, the instruments used during all major lung resections are: monopolar (e.g., Hook, Scissors) or bipolar instruments (e.g., Maryland) for dissection and graspers (e.g., Cadiere, Prograsp). The dissection of the hilar structures can be performed by the action of monopolar and/or bipolar instrument, while a grasper, inserted through the fourth arm, is used to retract the lung obtaining optimal exposition of the mediastinum. During the surgical procedure, CO_2 is insufflated (range, 5–8 mmHg) to drive the diaphragm down, enlarge the chest cavity and guarantee a good exposition of hilar structures.

Another aspect to take into account is the learning curve (the process of gaining experience and developing skills to make a procedure) of robotic surgery, some authors affirm that is shorter than that needed for traditional videothoracoscopic surgery. Gharagozloo *et al.* (6), Veronesi *et al.* (17) and Melfi *et al.* (18) suggested a learning curve of 20 robotic lobectomies for an experienced thoracic surgeon. Several studies suggest a wide range of cases (50 and 100/200) (19,20) to achieve a yield in VATS lobectomy. This difference between the Robotic and the VATS learning curves is likely to be due to the particular features of the robotic system that allow to perform the surgical procedures with the same approach and timing of the open surgery.

In our opinion it is mandatory to start the learning process with simple procedures such as for example, mediastinal lesions removal, and then to continue to more complex surgical interventions, such as lobectomies.

A further criticism raised against robotic surgery is the little data available about oncological radicality and survival with adequate follow-up period.

Indirect indicators of oncological radicality generally used are the number of lymph nodes resected and the lymph-nodal upstaging (the capacity to histopathologically identify metastatic lymph nodes clinically staged as negative), moreover, an adequate lymphadenectomy is essential to prevent under staging, with consequent lack of adjuvant treatment and worsening of prognosis. Nodal staging is therefore a surrogate of the quality of surgery. Two recent papers have shown a cutting point of 16 examined lymph nodes in the evaluation of the quality of LN examination or prognostic stratification postoperatively for patients with declared node-negative disease (21,22).

Discordant data exists on the radicality of nodal harvest during VATS lobectomies, more frequently, in fact, a lower median number of dissected lymph nodes are found and fewer nodal upstaging, particularly for the N2 group, when compared to open surgery (23-25).

Several authors reported their experience on analysis of lymph nodal upstaging in VATS procedures and thoracotomy resections, in most of the cases the studies reported a lower rate of upstaging in VATS group. D'Amico evaluated 189 patients underwent open lobectomy and 199 VATS lobectomy and observed different upstaging to N1/N2 between the two groups: 14.5% cases in the open group and 8.8% in VATS one (26). Also, Licht analysing 1,513 lobectomies for clinical stage I NSCLC performed by VATS or open surgery, confirms lower upstaging in VATS group than thoracotomy group (11.9% *vs.* 24.6%), although the mean number of dissected lymph nodes stations were similar and no difference in survival was showed between two groups (27).

Boffa and colleagues conversely in a report of 11,500 anatomic lung cancer resection from the Society of Thoracic Surgeon database showed a similar lymph nodal upstaging after VATS and open surgery (11.6% *vs.* 14.3%) (28).

Comparing lymph nodal dissection by VATS versus open surgery a critical aspect is the evidence of superior number of mediastinal nodes removed during thoracotomy procedures, probably due to the greater difficulty to reach comfortably all mediastinal areas with thoracoscopic instruments (29).

The dissimilar results between VATS and thoracotomy lymphadenectomy in comparative studies are probably related with different expertise and level of skills of the surgeons.

Conversely, several studies have demonstrated the equivalence between robotic and open nodal dissection. According to these studies, the median number of lymph nodes resected with robotic approach is the same of open surgeries (17,30).

In our opinion, the robotic approach gives also a better dissection than VATS in a confined space of enlarged N1 lymph nodes and a more precise N2 lymph nodes removal.

Wilson reported the first experience of upstaging in patients with clinical stage I NSCLC who underwent robotic lobectomies. In this study upstaging was observed in 10.9% of cases, especially in patients with larger lung tumor (31). Park reports a 21% rate of nodal upstaging (6,32) and Velez-Cubian *et al.* a 30% of overall upstaging rate (33).

Despite the controversy over lymphadenectomy data, the long term survival and disease free survival are similar in NSCLC treated by VATS and open surgery, confirming the effectiveness of the mini-invasive procedure (29,31,34,35). The outcomes oncologic results in robotic treatment for lung cancer are more recent than VATS, not many large studies on long-terms outcomes have been reported. Park shows an overall 5-year survival of 80% (32), Wilson a 2-year overall survival of 87.6% with a DFS of 70.2% (31) and Melfi a 5-year actuarial survival of 80% (36).

However, the most criticized aspect is represented by costs of robotic platforms. Several studies have been carried out to compare the costs of VATS, thoracotomy and Robotic procedures. In 2008, Park and Flores (37) conducted a retrospective review to determine the expenses associated with the resultant hospital stay. The authors found robotic procedures less expensive than thoracotomy ($4,380 *vs.* $8,368), but more costly than VATS ($1,479).

Cost control is a fundamental aspect for a healthcare system, and for this very reason in Pisa was created a multidisciplinary robotic centre. In order to minimize costs, the managerial strategy of our centre is based on high surgical volumes, complex procedures and standardization of the technique. After 6 years of experience, with the increasing number of the robotic procedures and thanks to the standardization of the technique (prefixed instruments, shorter docking time, dedicated team of surgeons, anaesthetists and scrub nurses) the centre has obtained a positive result: robotic surgery has been actually considered revenues from disease-related-groups (DRGs) (38).

When?

With regard to the indications of the robotic approach, we noticed that in the majority of cases robotic lung resection is offered to very selected patients, with early clinical stages (I and II) and no comorbidities, some authors also add dimensional criteria and exclude the lesions that are greater than 5 cm (18). Recently some authors have extended the inclusion criteria and have treated with a robotic approach patients with advanced stages, as clinical IIIA stage after neoadjuvant therapies (39), or have performed sleeve lobectomy or robotic bronchoplastic upper lobectomy (40).

A review conducted by Kent *et al.* (41) collecting data from 33,095 patients treated with open, VATS and robotic approach in eight countries between 2008 and 2010, has shown that in "high-volume surgeons" robotic lobectomy is associated with a reduction in mortality, length of stay and overall complication rate compared with thoracotomy. Robotic lobectomy is also associated with a statistically significant reduction in mortality compared with VATS lobectomy.

As regards as the quality of life (QoL), Cerfolio *et al.* (30) firstly reported an analysis on thoracic robotic surgery patients that shows a significantly higher average mental QoL score 3 weeks postoperatively compared to open surgery.

Louie and colleagues (11) declared that patients operated with robotic-assisted surgery used fewer painkillers and returned to daily life sooner than when compared with VATS. A recent study by Kwon *et al.* (42) has shown no significant difference in acute and chronic postoperative pain between VATS and RATS. Interestingly patients who underwent robotic surgery felt that the robotic approach affected positively their pain, indicating an important difference between real and perceived pain.

A recent study published by Park *et al.* (43) compared post-operative data and survival outcomes of patients treated with lobectomy after induction chemotherapy using minimally invasive approaches (VATS or robotic procedures) or thoracotomy. The results show a similar OS and DFS between the two groups, suggesting the feasibility of using minimally invasive approaches, following induction therapy, to treat selected locally advanced stages of NSCLC.

Doubtlessly, the use of robotic system in thoracic surgery is still evolving as well as its indications and applications.

Moreover, several studies suggest that perioperative outcomes, including postoperative complications, are similar between robotic and conventional surgery (44).

Conclusions

Robotic surgery for lung lobectomy is feasible, safe, provides several improvements both for the patient (mainly in terms of higher rates of lymph nodal upstaging with less operative morbidity) and for the surgeon (advanced features of robotic platform and reduced learning curve) when compared to open and VATS approach in specialized centres (45).

Regarding the most discussed aspect of robotic procedures, its high capital and running costs, we believe that a management's strategy based on high surgical volumes, complex procedures and standardization of technique could reduce the costs of robotic procedures.

Therefore, taking into account what has been said, the right question to ask should be: "why not"?

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Footnote

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Robotic surgery for lung resections—total port approach: advantages and disadvantages

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Abstract: Minimally invasive thoracic surgery, when compared with open thoracotomy, has been shown to have improved perioperative outcomes as well as comparable long-term survival. Robotic surgery represents a powerful advancement of minimally invasive surgery, with vastly improved visualization and instrument maneuverability, and is increasingly popular for thoracic surgery. However, there remains debate over the best robotic approaches for lung resection, with several different techniques evidenced and described in the literature. We delineate our method for total port approach with four robotic arms and discuss how its advantages outweigh its disadvantages. We conclude that it is preferred to other robotic approaches, such as the robotic assisted approach, due to its enhanced visualization, improved instrument range of motion, and reduced potential for injury.

Keywords: Lung cancer surgery; minimally invasive surgery; robotic surgery; total port approach

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Introduction

Compared to thoracotomy, thoracic minimally invasive surgery—such as video-assisted thoracoscopic surgery (VATS) (1-3) and robotic surgery (4-8)—offer improved perioperative outcomes as well as similar long-term survival for patients with early-stage non-small cell lung cancers. Robotic surgery offers several advantages over VATS, such as replacing restricted, two-dimensional images with magnified, high-definition, three-dimensional visualization while greatly enhancing surgical instrument maneuverability and precision (1,4,9). Given these advancements, robotic thoracic surgery has swelled in popularity, with robotic lung resections tripling over the last 2 years (10).

Despite the growing popularity of robotic thoracic surgery worldwide, published comparisons of different technical methods applied to robotic surgery remain scarce. Such information is vital to identify, better understand, and thereby improve upon best practices. This allows for the establishment of technical standards that can help, among other things, improve outcomes and reduce operative duration and cost. In particular, there remains much discussion regarding what constitutes an optimal robotic approach and its associated port placement, with techniques cited ranging from incomplete port approaches with VATS access incisions to total port approaches with three versus four arms (11-13). Naturally, it is important to expound upon the technical details involved as well as the respective advantages and disadvantages that each technique may provide (8). The objective of this paper is to illustrate our preferred port placement for a total port approach with four robotic arms and discuss its relative advantages and disadvantages for robotic lung resections.

Port placement

In our total port approach, we utilize all four arms of the da

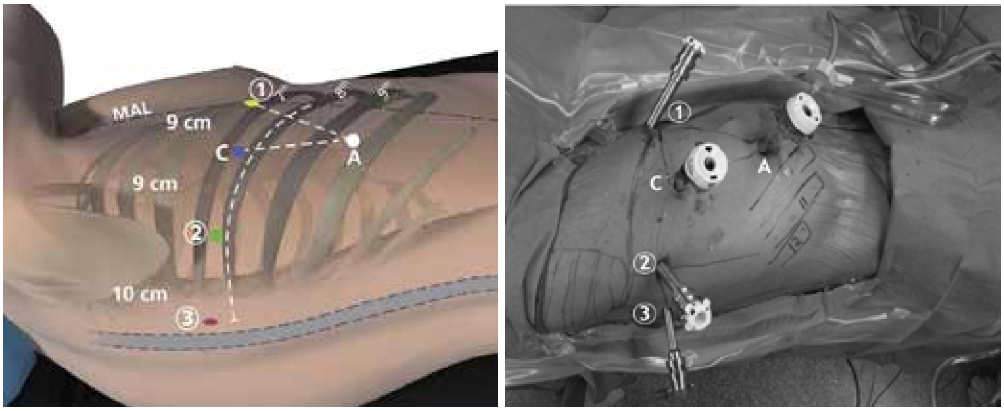

Figure 1 Total port approach with four-port placement for right-sided pulmonary lobectomy with da Vinci Si robotic arms 1, 2, 3, camera [C], and access port [A] [Reprinted with permission (15)].

Vinci Si or Xi robot. Our port positioning and placement is systematic and optimized for robotic arm maneuverability (8,14,15) (*Figure 1*). For the da Vinci Si system, we use two 8 mm ports (left and right robotic arm ports), a 12 mm port (camera), and a 5 mm port (fourth robotic arm port—we use the smallest size port because it is all that is required for the fourth arm instrument, allowing us to minimize pain); for the Xi system, all the ports are 8 mm ports. We also utilize a 12 mm assistant port that can be used for stapling and exchange of items such as rolled-up sponges and vessel loops. The assistant port is also important in case sudden or catastrophic bleeding occurs. The following is a description of port placement for a right-sided resection.

We place the ports in the seventh (upper or middle lobectomy) or eighth (lower lobectomy) intercostal space. The fourth robotic arm is located 2–3 cm from the spine, the left robotic arm port is located 10 cm away from that port, the camera port is located 9 cm from the left robotic arm port, and the right robotic arm is located 9 cm away from the camera port (*Figure 1*). The port locations are marked beforehand, although slight changes to these locations are often necessary once the intrathoracic anatomy is visualized. The first port to be placed is the camera port [C]. To verify pleural space entry, a camera is introduced into the port before insufflating the thoracic cavity with warmed, humidified carbon dioxide to inferiorly displace the diaphragm and maximize the cavity size. Next, in an effort to reduce postoperative pain, we administer a subpleural paravertebral block of ribs three to eleven using 0.25% bupivacaine with epinephrine via a 21-gauge needle. Then, the fourth robotic arm port (labeled “3” in *Figure 1*) is placed. This port is inserted two ribs beneath the oblique fissure (often over the top of the eighth rib for upper lobectomy and over the top of the ninth rib for lower lobectomy) at a maximally posterior location about 2 cm anterior to the spinous processes of the vertebral bodies; it will control the second left hand instrument. The camera is then placed through the fourth robotic arm port before inserting the final two robotic ports for the left (labeled “2” in *Figure 1*) and right (labeled “1” in *Figure 1*) robotic arms under direct vision. The assistant port is a 12 mm port and is inserted just superior to the diaphragmatic fibers—and hence as anteroinferior in the chest as possible—while being triangulated between the camera and right robotic arm ports. This isosceles triangle positioning maintains excellent robotic arm maneuverability while securing adequate space for the bedside assistant.

There is a degree of flexibility in the assistant port’s position, if warranted anatomically, as it can also be triangulated between the left robotic arm [2] and camera port [C]. In either case, the purpose is to make this isosceles triangle maximally wide and deep, thereby allowing for both extensive robotic arm dexterity and space for the bedside assistant to work. Lastly, for the Si system, the camera port [C] incision is enlarged to a 12 mm double-cannulated port, enabling it to admit the robotic camera.

Once the ports have been secured, the Si robot is steered at a fifteen-degree angle over the patient’s shoulder and its arms are attached to the respective ports (one through four) as noted (8,14,15). For the Xi system, the robot can approach the operating room table perpendicular to the patient, after which the beam is rotated to the proper position.

The robotic instruments we use most commonly for lung segmentectomy are a bipolar curved tip dissector in right robotic arm, a Cadiere grasper in the left robotic arm, a lung grasper (Si system) or tip-up fenestrated grasper (Xi system) in the fourth robotic arm, and a zero-degree camera in the camera port.

Advantages and disadvantages

The total port approach for robotic surgery for lung resections comes with several distinct advantages over a robotic assisted approach. The total port approach is by definition a completely closed environment (8,14,15). This allows for the introduction of warm humidified carbon dioxide for thoracic insufflation, providing a myriad of benefits. Among them, it spares the lungs from exposure to the operating room's cool, dry air (15). It also expands the thoracic cavity by decreasing the size of the lung parenchyma and pushing the diaphragm inferiorly (15). As a result, the space with which to visualize the thoracic anatomy—including mediastinal nodal views—is augmented (11). Moreover, the space in which robotic instruments can be manipulated is optimized, enabling more efficient and effective surgery. Pushing the diaphragm downwards with carbon dioxide insufflation also reduces potential for injury to it intraoperatively (15). We further believe that the use of carbon dioxide insufflation saves time, both by improving visualization (as aforementioned) as well as decreasing bleeding from the lung parenchyma via increased intrathoracic pressure.

Our port placement facilitates this enhanced visualization, and we take full advantage of the expanded room by using four robotic arms, equipping the surgeon to retract the lung with the fourth arm rather than relying on the assistant to do so. Given that retraction is critical for properly exposing hilar structures to be dissected, isolated, and divided, we believe that this also saves time and increases our level of efficiency compared to a three-arm technique. We additionally verify each port's insertion point from the interior (after the first port) to reduce potential for injury, and try to place ports two, three, and four along the same rib in part to avoid damaging multiple intercostal neurovascular bundles (11,15). We use a zero-degree camera, which has less torque than a thirty-degree one, to further decrease the chances of intercostal nerve injury (8,14,15). Vitally, the total port approach eschews the morbidity of a utility thoracotomy incision and avoids the inefficiency of regularly switching from robotic to VATS resection during the operation (12,13).

However, the total port approach does carry some disadvantages when compared to a robotic assisted approach. Perhaps most significantly, the total port approach's completely closed environment does not allow for inserting a finger into the chest (15). This is traditionally used for direct palpation of a nodule or the lung, helping to locate an area of interest. That said, several alternate methods—such as electromagnetic navigational bronchoscopy with tattooing using a marker such as methylene blue or indigo carmine—allow for precise nodule targeting without necessitating direct palpation, and can be readily accommodated with our approach (16). In addition, near-infrared imaging of intravenously-administered indocyanine green can be used to detect lung nodules; this capability is integrated into the da Vinci Xi platform (17). Finally, if it is indeed felt to be imperative in select cases, our technique does not contraindicate an additional small access incision for this purpose. While there is voiced concern for a supposed inappropriateness of a completely portal operation—with reasons ranging from cumbersome dissection to increased risk for catastrophic bleeding—we have demonstrated this to simply not be the case, with a 10% postoperative complication rate, 2% major morbidity rate, and 0% 90-day mortality rate in our published consecutive series of one-hundred planned robotic segmentectomies (7,15). In terms of three-arm versus four-arm approaches, there is the hypothetical disadvantage of added pain from the additional incision made in the chest for the four-arm approach. That said, there have been no studies comparing pain levels or narcotic usage between the two techniques. In addition, there can be greater potential for collision of instruments outside the body when using the additional arm; this can, however, be minimized with proper attention to the spacing and placement of ports, as we have detailed. The advantages and disadvantages of a totally portal four-arm robotic approach to lobectomy are shown in *Table 1*.

Discussion

Minimally invasive surgery offers improved perioperative outcomes as well as similar long-term survival when compared with open thoracotomy in the treatment of early-stage non-small cell lung cancers (1-3,8). Specifically, robotic lobectomy as compared to open thoracotomy has been shown to have decreased rates of morbidity—including air leak, blood loss, blood transfusions, and chest tube duration—as well as reduced length of hospital stay (10,18). Robotic lung surgery offers improved visualization with

Table 1 Advantages and disadvantages of totally portal four-arm approach to robotic lobectomy

Advantages	
Carbon dioxide insufflation	
Warmed, humidified air	
Improved visualization	
Decreased bleeding	
Decreased risk for diaphragmatic injury	
Fourth arm available for retraction	
Smaller incision than if utility port used	
No need to switch between robotic and VATS techniques	
Disadvantages	
No way to palpate the lung	
Added pain from fourth incision	
Increased risk of collisions with extra arm	

VATS, video-assisted thoracoscopic surgery.

its magnified, high-definition, three-dimensional images, allowing for a level of anatomic appreciation that cannot be replicated by VATS or even open thoracotomy. In addition, robotic arms and their instruments can be manipulated with more degrees of articulation than their VATS counterparts. With the advent of robotic stapling, the argument that VATS has a greater variety or range of instruments has become weaker. The ergonomics of robotic surgery, where the surgeon is sitting at the console rather than standing, and the motion scaling that decreases the tremor of the surgeon's hands, are other benefits of robotic technology. Disadvantages of robotic surgery include cost, potentially increased duration of operation, and complexity in terms of logistical needs, training, and equipment.

Just as with VATS lobectomy, multiple techniques for robotic lobectomy exist. Dylewski and Ninan have described a completely portal three-arm approach in 74 patients (11). Veronesi and Melfi have described an incompletely portal robotic assisted approach that utilizes four robotic arms as well as a VATS access incision in 54 patients (12). Gharagozloo, meanwhile, has reported on a hybrid approach in 100 patients (13). Our extensive experience in robotic surgery for lung resections, including 520 robotic lobectomies between February 2010 and December 2015, has allowed us to develop and fine-tune a regimented process for port placement via the total port approach with four robotic arms. In essence, our strategy is optimized to achieve several goals: (I) to operate with an emphasis on safety and minimizing postoperative complications; (II) to maximize maneuverability for robotic instruments and improve operative precision; (III) to improve efficiency and reduce operating room time and cost; and (IV) to improve patient outcomes.

We favor a completely portal four-arm approach for the benefits outlined in this paper. By maintaining a completely closed environment, the thorax can be insufflated with warm, humidified carbon dioxide, safely enlarging the operative environment while helping protect the lungs. This enables enhanced visualization and facilitates efficient and effective surgery. However, it also carries some disadvantages, including the presence of an additional incision, greater potential for instrument collisions for the inexperienced practitioner (four-port versus three-port technique), and the inability to directly palpate the lung or a nodule secondary to the completely closed environment (completely portal versus a utility incision technique). Notably, though, alternatives for nodule identification exist and are becoming more widely studied and adopted.

Our total port approach with four arms, and the meticulousness with which we have adjusted and detailed our port placement, has developed over several years of efforts to improve our robotic lung resections. This documented experience is a strength of this paper. A necessary limitation of this paper is that it relies largely on the experience at a single institution, making its generalizability unproven. In addition, the fact remains that the objective benefits of one robotic lobectomy technique over another have not been systematically studied. That being said, we have striven to expound upon not only the intricacies of our preferred port placement but also the reasoning behind our decisions, so as to allow surgeons to adapt our model to individual patients as they deem appropriate. Likewise, we have offered some potential modifications for select situations. Future study from multiple thoracic robotic surgeons and multiple centers is needed to further explore the advantages and disadvantages of the total port approach with four robotic arms as compared to its alternatives. We have attempted to position this paper as a basis from which thoracic robotic surgeons can expand upon, improve, and then document their refinements to our techniques, and we look forward to their input.

Conclusions

In conclusion, robotic thoracic surgery is a growing field in which there remains a great need for demonstrably effective and efficient technical methods. We have elucidated our strategy for the total port approach with four robotic arms and explained why it is our favored approach for robotic lung resections.

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Footnote

Conflicts of Interest: OI Ramadan: none; B Wei: Medtronic—speaker; RJ Cerfolio: Intuitive Surgical—proctor, speaker, lecturer; Ethicon—speaker, teacher; Community Health Services—consultant; KCL—consultant; Bovie—consultant; C-SATS—consultant.

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Catastrophes and complicated intraoperative events during robotic lung resection

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Abstract: Intraoperative complications and catastrophes are an accepted and perhaps inevitable aspect of all surgeries. Anatomic pulmonary resection puts in close proximity the tracheal-bronchial tree, pulmonary vasculature, heart and great vessels within the small volume area of the chest. Fortunately, major complications and catastrophes are uncommon regardless of surgical approach. Pulmonary arterial injury is the most frequently reported. Most injuries necessitate a thoracotomy for definitive management though novel techniques are emerging for minimally invasive management. This section focuses on intraoperative pulmonary artery and vein injuries, major airway injuries and transections, injuries to major abdominal organs and effects of carbon dioxide insufflation during robotic pulmonary resection.

Keywords: Lung resections; VATS; robotic surgery; complications; intra operative

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Introduction

Intraoperative complications and catastrophes are potential problems in any surgery. During anatomic pulmonary resection the close proximity of the tracheal-bronchial tree and pulmonary vasculature located in the small volume area in the center of the chest juxtaposed to the heart and great vessels create a unique set up for such events to potentially occur. Although the incidence or occurrence of such events, fortunately, is very uncommon during anatomic pulmonary resection be it via thoracotomy, VATS or robotics, these complications are responsible for nearly one quarter of the in-hospital mortalities (1-3). During the transition from thoracotomy to VATS, concerns were raised that the closed chest VATS approach was potentially problematic because to execute vascular control would require too much time to get into the chest. With the advent of robotic lobectomy, those same concerns and risks exist but now the surgeon is present only in the room but not scrubbed at the bedside.

While intraoperative complications/catastrophes are inevitable no matter how skilled the operative surgeon is, the experienced surgeon is always aware of their existence, tries to anticipate their development, is prepared to act in an instant but keen to prevent such problems from occurring (3). And, while all thoracic surgeons are prepared to tell you about "the time such and such happened", the literature documenting the incidence and articulating the solutions to these events is sparse regardless of surgical approach. These types of complications are not captured by any major society or administrative database (2) and the individual surgeon or team is unlikely to have a large series. As such research attempting to delineate the incidence and causative factors is nearly impossible to perform.

In this paper, the focus will be on intraoperative pulmonary artery and vein injuries, major airway injuries, inadvertent transections, injuries to major abdominal organs and effects of carbon dioxide insufflation during robotic pulmonary resection. Given the similarity with VATS lobectomy and the sparse literature, experiences and solutions for similar events are presented from both approaches in order to draw upon the entire minimally invasive experience.

Table 1 Major vascular injuries during robotic and video-assisted thoracoscopic surgery anatomic lung resection

Authors	N	Conversion (n%)	PA (n%)	PV (n%)	Transections (n%)	Etiologies [n]
Robotic						
Cerfolio *et al.* (1)	632	39 (6.2)	15 (2.4)	–	–	During dissection [10]; stapler [5]
Toker *et al.* (4)	102	4 (3.9)	2 (2.0)	–	1 (1.0)	–
Adams *et al.* (5)	120	4 (3.3)	1 (0.8)	–	–	–
Melfi *et al.* (6)	229	23 (10)	1 (0.4)	2 (0.8)	–	–
Dylewski *et al.* (7)	197	3 (1.5)	1 (0.5)	-	–	–
Yang *et al.* (8)	172	16 (9.0)	3 (1.7)	–	–	–
VATS						
Decaluwe *et al.* (3)	3,076	170 (5.5)	88 (2.9)	–	9 (0.3)	–
Augustin *et al.* (9)	232	15 (6.5)	6 (2.6)	–	–	Tumor size/locale; stapler
Mei *et al.* (10)	414	11 (2.7)	11 (2.7)	3 (0.7)	–	Scissor dissection; stapler [4]; blunt dissection
Flores *et al.* (2)	633	13 (2.0)	2 (0.3)	1 (0.2)	3 (0.5)	–

Figure 1 Holding pressure with pre-rolled up sponge.

Pulmonary vascular injury

Pulmonary arterial injury

The most common intraoperative catastrophe during anatomic pulmonary resection is an injury to the pulmonary artery (*Table 1*). The incidence is reported to occur in 0.5% to 2.6% in series of greater than 100 robotic lobectomies (1,4-8) and from 1 to 2.9% of VATS lobectomy (2,3,9,10). In most cases, this injury was also the primary reason for emergent/urgent conversion from a minimally invasive approach to thoracotomy. In most series the minority of cases were being managed with a minimally invasive approach (1,3). However, one VATS series suggests that over 80% can be managed minimally invasively with a novel technique of angiorrhaphy (see below) (10). The upper lobes were the most common site of injury during robotic cases owing to the multiple arterial branches on the left, the large truncus on the right and the fact that these sites are favored in lung cancer (1,3).

Injuries to the pulmonary arterial system occur from a variety of events and situations. Surgeon experience does not seem to influence the incidence of this injury (3). Most commonly it appears to occur during blunt and sharp "dissection" of the artery but it is not always reported under which circumstances this might be occurring. It is recognized that patients receiving induction chemo and/or radiation therapy and larger tumor size are at greater risk for an arterial injury though the numbers are small (3,9). Injuries are also noted to occur around the time an endovascular stapler is applied and fired leading to staple line bleeding or more central tears (1,9,10). Lastly, the presence of calcified lymph nodes requiring dissection also creates risk for an injury (2).

When an injury occurs, the initial response from most surgeons is one of fright and a surge of catecholamine. In series that described their management of an injury, all cited the need to remain calm, poised and in charge (1,10,11). The first step is applying pressure on the injury. This can be accomplished with the overlying lung, using one or two pre-rolled sponges (1), inserting a sponge stick or using pressure via a blunt tipped suction device (10) (*Figure 1*). After obtaining control, its crucial to inform the anesthesiologist, nursing team and request assistance from surgical partners is critical. We have found as have others (1) that maintaining pressure for 5–7 minutes by the clock often allows the team to get organized but it also allows one to differentiate the degree of injury since some will stop with simple pressure.

When the team is ready, pressure control can be transferred to an external bedside assistant and the camera port undocked so the camera is free to maintain a visual on the site. Then, the remaining robotic instruments can be removed, the robot undocked and safely moved aside. A standard posterolateral thoracotomy can be performed under controlled circumstances while pressure is applied and the camera to visualize is left in place. Once inside the thoracic cavity, surgeons can proceed as they would in an open situation—proximal and distal control followed by a determination on repair, ligation or transection.

Figure 2 Pressure with rolled sponges can facilitate control of bleeding and allow for stapler division. Courtesy of Dr. Robert Cerfolio (12).
Available online: http://www.asvide.com/articles/1449

In the majority of cases and surgeons, there is no other option except to proceed with conversion to thoracotomy in hopes of salvaging the resection, preserving life and then lung parenchyma. With increasing experience, we have observed, as have others, that the sponge and pressure can be slowly released to see what volume of bleeding ensues (*Figure 2*). If the bleeding has stopped the surgery could simply continue. Or, if minimal or persistent low volume bleeding continues and the injury can be discerned it may be possible to control the injury with surgical clips, stapling more proximally or intra-corporeal suturing. This decision requires weighing multiple factors such as the patient's status, oncologic outcomes, access and feasibility and the threat to patient life.

Mei and colleagues (10,13) recently reported on a novel sequential VATS technique that allowed over 80% of vascular injuries to be controlled minimally invasively. This requires control with pressure from a suction device. This can then be followed by placement of a series of sutures on either side of the suction device allowing the injury to be closed (*Figure 3*). Alternatively, the suction device is replaced with an Allis clamp for control followed by mattress sutures (*Figure 4*). In extreme circumstances, a vascular clamp is applied proximally with the Allis clamp for greater control followed by sutures. (*Figure 5*). This technique may be translatable to robotic lobectomy but require an additional port to allow the Allis clamp to be inserted and the surgeon will require skills to suture inside the chest.

Pulmonary vein injury

Injury to a pulmonary vein is much less common than a pulmonary arterial injury. Several series have reported its

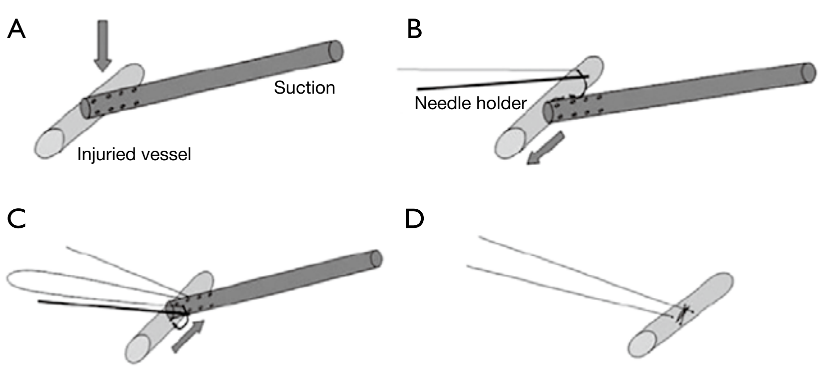

Figure 3 Technique for suture closure of a vascular injury using a suction device. (Reprinted from *Surgical Endoscopy* and reference the Mei paper.)

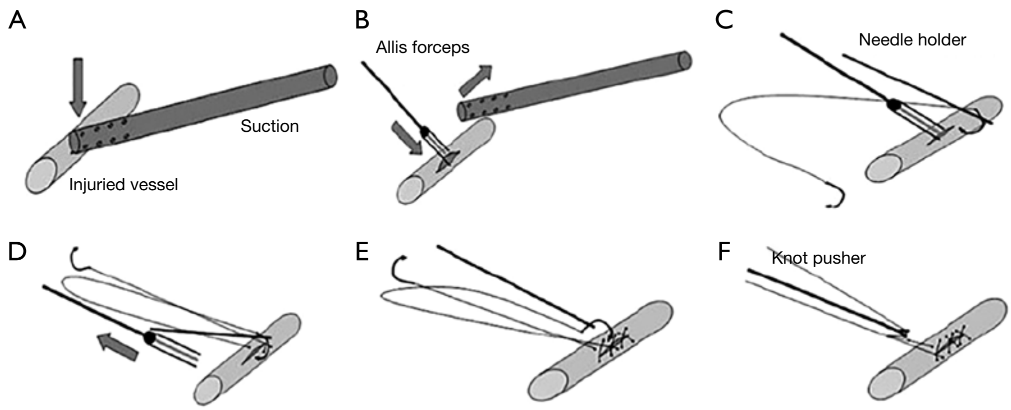

Figure 4 Technique for suture closure of a vascular injury using a section device and Allis clamp. (Reprinted from *Surgical Endoscopy* and reference the Mei paper.)

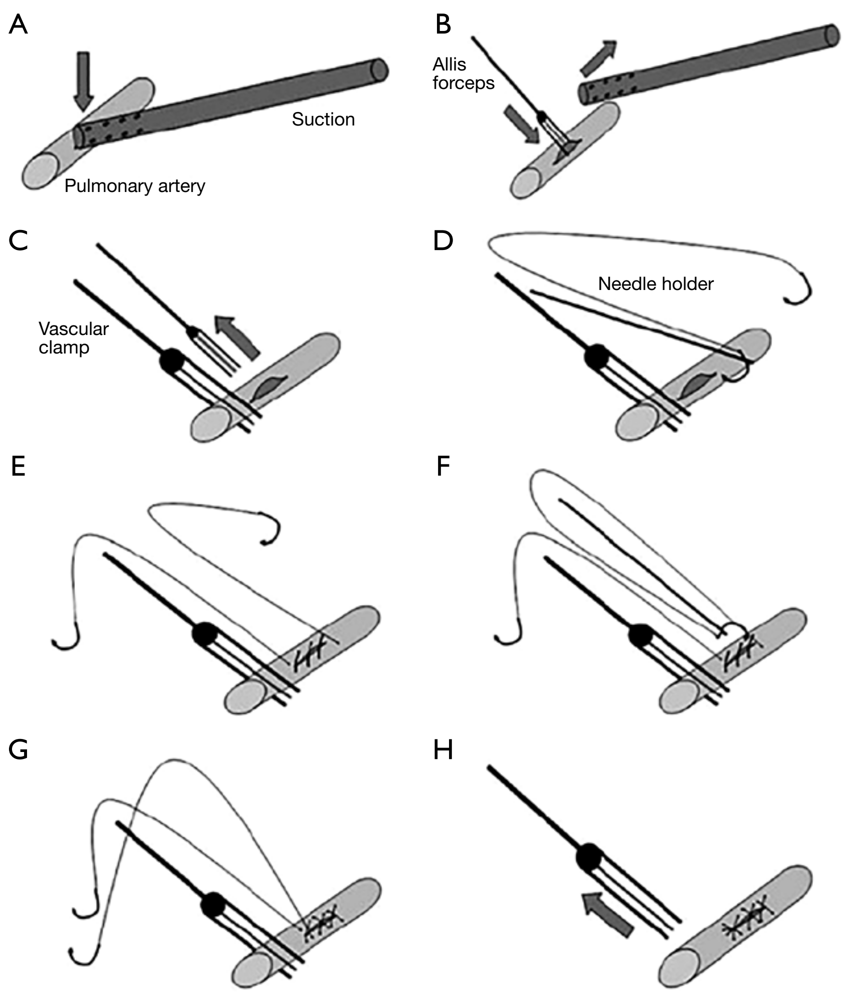

Figure 5 Technique for suture closure of a vascular injury using a section device, Allis clamp and proximally placed vascular clamp. (Reprinted from Surgical Endoscopy and reference the Mei paper.)

occurrence but no details are provided on the etiology (2,6,10). In one VATS case, a staple line dehiscence occurred when the pericardium was inadvertently caught in the staples. This was managed with a thoracotomy and intrapericardial oversewing of the defect (2).

Great vessel and thoracic duct injury

The superior vena cava, azygous vein, thoracic aorta and thoracic duct are all structures that reside within the thoracic cavity in continuity with the lung. Therefore, they are potential structures that may be injured during robotic lung resection. Fortunately, since the majority of minimally invasive lung resections are carried out for relatively early stage disease, these structures are rarely injured. However, with increasing experience and as surgeon's tackle more advanced disease, these structures will be potential structures that can be injured.

The most commonly injured structure is the thoracic duct. This usually occurs as a result of an extensive lymphadenectomy in the subcarinal region as the duct passes from its position between the aorta, the azygous vein and the vertebral bodies in the right chest to cross and ascend toward the left subclavian vein. Occasionally, it will be exposed during decortication from a prior pleural process during mobilization of the lung. If chyle is identified during resection, the duct can be directly clipped or ligated or alternatively, en mass ligature at the aortic hiatus can be performed. More commonly, it is identified as a modestly high output chest tube drainage that turns milky with institution of oral diet. Standard treatment algorithms apply but we tend to favor early return to the operating room for ligation when the output approaches or is greater than 500 mL/day.

Although injuries have been reported to the azygous vein and superior vena cava during minimally invasive lung resection the true incidence is unknown (2,10). In one reported series, an injury to the azygous-caval junction occurred during resection of station 4R lymph nodes and was repaired successfully by thoracotomy. The mechanism was not reported but it is possible that this was related to traction or thermal/cautery injury (10). In the other series, two superior vena caval injuries are reported during right lower lobectomy for which both were repaired via a VATS approach. Unfortunately, no further details were provided.

Erroneous transections

Inadvertent transections or divisions of uninvolved structures in the pulmonary hilum occur primarily in situations with distorted anatomy due to scarring or a centrally placed tumor. In three VATS transections involving the proximal or main pulmonary artery, the incident was recognized immediately. In each case the patient underwent thoracotomy with resection of the tumor. In two cases, the arterial supply was reconstructed and in the remaining case a pneumonectomy was required (2). In one robotic series, an inadvertent transection of the pulmonary artery occurred during a resection after chemoradiotherapy to 60 Gy. This patient underwent thoracotomy and sleeve resection of the pulmonary artery (4).

The pulmonary vein is also prone to inadvertent transection. In one VATS series the middle lobe vein was most commonly the structure transected for no apparent reason other than failure of recognition; however, when an upper or lower vein was transected the common finding was either a centrally placed tumor and/or the use of induction chemoradiotherapy (3). Most authors noted the importance of clearly identifying and delineating the lower lobe vein as a separate entity from the upper vein as one method for avoiding an erroneous transection. Once the injury occurred, a thoracotomy was performed and the lower or upper veins were reimplanted if appropriate. If the middle lobe vein was transected, conversion was not performed but bilobectomy was completed (3).

Inadvertent transections of the airway have also been reported. Mostly commonly the bronchus intermedius was transected during lower lobectomy necessitating bilobectomy (3). In another VATS series, the middle lobe bronchus was divided during upper lobectomy due to a challenging anterior fissure. This also necessitated a bilobectomy (2).

Tracheal-bronchial airway injury

An injury to the uninvolved airway, proximal trachea or contralateral main stem bronchus is unusual and rare. In the reported series, the most common etiology was the double lumen endotracheal tube causing a tear in the main bronchus either from over inflation of the balloon and during manipulation of the tube. However, injuries have also been reported to occur during dissection around the middle lobe during VATS bilobectomy, during stapling of the lower lobe bronchus and nodal dissection in the subcarinal space along the bronchus intermedius (2,3). These were all managed by thoracotomy, primary repair with buttress or more proximal resection.

Gastrointestinal organ injury

Injuries to the adjacent esophagus or sub diaphragmatic liver and spleen are uncommon. The esophagus can become involved as in innocent bystander during nodal dissection in the subcarinal (station 7) or station 9 usually from an electrocautery injury and less commonly from direct laceration (3). In one reported case, VATS nodal dissection was thought to be the causal factor leading to an esophago-bronchial fistula 6 weeks after resection. This was initially treated with a thoracotomy and muscle interposition (2). Occasionally, the stapler tip has been reported to be the cause of inadvertent trauma to the esophagus (3). Treatment depends on the severity of injury and can involve simple suture closure to formal two-layer repair with a buttress reinforcement flap.

Solid organ injuries primarily to the spleen but also the liver occur rarely. These injuries are thought to be caused by low port placement, misaligned stapler tips entering the chest and cautery arcing via the diaphragm (2). We favor placing the most anterior port (6–7th intercostal space, anterior axillary line), which becomes our chest tube site, as the first port so that lower ports are placed under direct vision and hopefully avoids these rare injuries. Treatment options depend on the injury and blood loss but include observation, embolization and lastly operative splenectomy/splenorrhaphy and packing (3).

Miscellaneous complications

There are a variety of very unusual or rare complications that necessitate further surgery that most thoracic surgeons are aware of but are rarely reported. These include lobar torsion, massive parenchymal air leak after decortication in preparation for resection and airway kinking (3). The treatment of these complications is not standard and based on individual surgeon judgment. Lastly, cardiac arrhythmias occasionally occur such as ventricular tachycardia or atrial fibrillation (3).

Effects of CO_2 insufflation

One unique feature of robotic lobectomy is that CO_2 insufflation is often used particularly during completely portal procedures. During VATS resection this is rarely used. As such several complications can arise from its use including CO_2 embolus, compromised venous return, severe brachycardia or progressive arterial desaturation and acid-base disturbances secondary to hypercarbia (14). It is important that thoracic surgeons performing robotic surgery with CO_2 insufflation be aware of these rare events because as the laparoscopic surgeons have discovered these occur rapidly as in the case of CO_2 embolus or insidiously over the course of the case creating physiologic disturbances that can prevent extubation. These events can be limited by keeping the flow and set pressure of CO_2 as low as possible to allow for visualization. Often, once the lung is deflated the need for CO_2 is negligible and can be turned off. One additional reason to stop the flow of CO_2 early is that in a swine model it appears to limit blood loss via application of pressure on the vessels which when released can potentially bleed (15).

Conclusions

Intraoperative complications and catastrophes during pulmonary resection are uncommon but can result in significant consequences for the patient. There is a paucity of reported experiences during robotic lobectomy. Even in the more mature VATS lobectomy experience, these complications are very uncommon. Robotic surgeons regardless of experience should have a "fire drill" plan for the rare event so that the team members understand their roles during these events. To increase learning and understanding VATS and robotic lung surgeons are encouraged to pool their results and report these events and their management.

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Footnote

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Robotic lung resections: video-assisted thoracic surgery based approach

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Abstract: Advances in technology cause major developments in minimally invasive thoracic surgery practice. The expected benefits of minimally invasive pulmonary surgery are clear and mostly as follows; shorter hospital stay, fast recovery, less pain, and decreased morbidity and mortality. Robotic surgery with improved visualization and instrumental technical capabilities has become an attractive tool for surgeons who are performing lung resections. However, robotic surgery still seems far away from standardization even in the basic fundamental which is "the best approach for docking". In this article, we would like to share our experience in robotic surgery with video-assisted thoracic surgery (VATS) based or in other terms "robotic-assisted" approach, and discuss its advantages and disadvantages. We speculate that, especially at early experience, VATS based approach or "robotic-assisted approach" may provide a smooth start up with the support of the experienced table surgeon.

Keywords: Robotic-assisted thoracic surgery; video-assisted thoracic surgery (VATS); lobectomy, segmentectomy

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Introduction

Video-assisted thoracic surgery (VATS) lobectomy started in the first half of 1990s, and two decades were necessary for VATS lobectomy before becoming a mature procedure in the early stage lung cancer. Despite long debates and negative attitude of experienced thoracic surgeons, VATS lobectomy established its place in the field of thoracic surgery.

Most of its difficulties were due to long learning curve of handling hilar dissection in a closed chest cavity. Long learning curve may be due to the lack of binocular visual system and wristed instrumentation. In addition, a camera controlled by another surgeon may be one of the reasons of the long learning curve. Robotics enabled rapid adoption in minimally invasive approaches for pelvic, cardiac and colorectal surgery, where vision and maneuverability are limited with open and laparoscopic approaches. In the past 10 years, robotic surgery has been adopted by thoracic surgeons unequivocally, and proved to have at least similar or better outcomes compared to VATS or open surgery, in terms of lower rate of complications, less blood loss, shorter hospital stay, less pain, and faster return to normal quality of life (1-4). Fast learning curve, provided by high definition three-dimensional camera, enhanced surgical maneuverability and precise surgery, has developed robotic lung surgery in the past 5 years. We have completed 5 years of active practice in the field of thoracic surgery with more than 250 cases. The aim of this study is to share our experience with VATS based approach.

In order to benefit from abovementioned superiorities, a surgical technique to dock is needed. This technique should provide the followings: Easy, uncomplicated and a platform

Figure 1 Positioning of the patient.

Figure 2 The location of posterior port in a left-sided resection. Note the relation with the camera port.

Figure 3 The incisions and the wound retractor covered anterior access incision.

to obtain the best capabilities of the robotic arms. Then, there remains a discussion regarding the optimum approach for the port placement. The debate is mostly on total port approach versus VATS based approach. VATS based approach is a "robotic-assisted approach" which is supported mostly by a table surgeon and an access thoracotomy. Each technique has its advantages and disadvantages. This paper aims to discuss the VATS based approach.

Technical details in VATS based approach

The patient is ready after the confirmation of single-lung ventilation with the fiberoptic bronchoscope, and the lateral decubitus position is given (*Figure 1*). The table is tilted either anteriorly or posteriorly, or kept in neutral position depending on the type of resection to be performed. The hilum of the lobe or the segment which was aimed to be resected is the target. Three ports were opened while trying to keep 10 cm between each port and 10–15 cm from the target. In VATS based approach the camera is in the middle and right and left arms 10 cm or more away lateral and medial to the camera. VATS triangle is usually kept as in a diamond shape, in which the target is the apex and the camera is the base. The camera is placed in the middle port. The technique we described here is used for Da Vinci SI Systems.

We firstly prefer opening the camera port on the 8th midaxillary intercostal space. While opening other ports, a 30 degree up camera is used. The second port is opened at the 8th or 9th intercostal space approximately 10 cm away from the camera port, and located close to the paravertebral sulcus (*Figure 2*). The anterior port is selected to be in a higher location like 6th or 7th intercostal space anterior to the camera port (*Figure 3*). All ports are opened following preemptive intercostal Marcaine injection. In the upper lobectomies and segmentectomies of the upper lobes, the access port is opened at the posterior intercostal space in the 10th or 11th intercostal space, after the docking has been completed as the 4th incision. In this case, anterior port is only for the right robotic arm. The robot is docked from the posterior by keeping 30 degrees between the vertebral column of the patient and transverse axis of the cart (*Figure 4*). Keeping the robotic camera in the up position, all the ports and instruments were placed safely. The service port was opened at the 10th–11th intercostal space at the posterior part of the thoracic wall to be used for suctioning, retracting, and taking the specimens out in upper lobectomies and segmentectomies of the upper lobe. This

Figure 4 Docking of the robot for a left-sided resection.

Figure 5 Wound retractor and share of the port with the table surgeon and robotic arm.

Figure 6 The table surgeon could do retractions, suctions from the same port.

port is covered with Alexis soft tissue skin retractor (Applied Medical, Rancho Santa Margarita, CA, USA). Right after docking has been completed, intercostal nerve block was performed immediately with the aim of having preemptive analgesia. The rest of the operation was performed with the camera in the down position.

Lower lobectomies and lower lobe segmentectomies

All three ports are opened in a similar fashion as described above, except for that the anterior port is opened as the access port, and it was covered with ALEXIS soft tissue skin retractor (Applied Medical, Rancho Santa Margarita, CA, USA) (*Figure 5*). By this way, the anterior arm (left in left sided resections and right in right sided resections) could be de-docked and re-docked easily whenever a stapler is introduced to provide the best environment for the table surgeon. Aspiration or retraction could be maintained by sharing this access port with the arm of the robot (*Figure 6*).

Standard flow of the operation in the VATS based approach

Maryland or curved bipolar forceps for the right arm and prograsper for the left arm were used, and the positions were changed as needed. First thing we do is to perform intercostal nerve block at 5–6 levels before starting the operation. During the resection and lymph node dissection, all the resected materials were extracted through the service port which was covered with ALEXIS soft tissue skin retractor (Applied Medical, Rancho Santa Margarita, CA, USA), and the main tissue containing the tumor was extracted using a plastic endobag. Individual dissection and division of the hilar structures were performed with endoscopic staplers introduced through the service port unless a specific introduction was needed, from either the right or left robotic arm ports. The incomplete fissures were divided either with a stapler introduced by the assistant surgeon through one of the ports, or with bipolar cauterization. Segmentectomies have been similarly performed (5,6).

Advantages

This approach is ideal for novices experienced in the VATS surgery. First of all, for an experienced VATS surgeon, converting to VATS is easy without any need for a thoracotomy. It carries similarities with the VATS technique and allows a VATS surgeon to feel comfortable in case of need to convert to a VATS operation instead of a thoracotomy. Especially when the surgeon wants to feel the

Table 1 Comparison of techniques, requirements, capabilities and outcomes.

Points	VATS based approach	CPRL
Console surgeon	VATS experience, may be better for starters	Experienced robotic surgeon
Table surgeon	Experienced surgeon is advantageous	No need for experienced table surgeon
CO_2 insufflation	Not useful	Very useful
Conversion to VATS	Easy to convert to VATS	Conversion to a thoracotomy
Palpation of the nodule	Possible and easy	Impossible
3 arms *vs.* 4 arms economy	3 arms easier	Almost always four arms
Pain	Not demonstrated benefit	Not demonstrated benefit
Length of stay	Similar	Similar
Conversion rates	Similar	Similar

VATS, video-assisted thoracic surgery; CPRL, completely portal robotic lobectomy.

tissue resistance during dissection, dissection of a particular vessel may be provided by the VATS based approach. The second most important benefit is to allow palpation of the nodules to be wedged which is almost always impossible in the total port approach. The third important advantage is as two arms are used, this operation is cheaper than the total port approach. There is also hypothetical advantage of less pain compared to four ports approach due to lesser incisions. The anterior incision has always has a potential to convert it to an appropriate thoracotomy is the last advantage.

Since we have a long standing experience in the VATS anatomical lung resections and thymectomy operations, we preferred to start with the VATS based approach. Now, after establishment of an experience level we can also perform total port approach. We speculate that total port approach necessitates a level of expertise in the field of robotic surgery which could be provided with duration of VATS based approach.

Disadvantages

If the table surgeon is a standard surgeon and developed capabilities, including de-docking and re-docking and vessel stapling, VATS based approach is extremely safe. However, if the table surgeon is novice, if it is a kind of duty to be done by a shift system, VATS based approach may be cumbersome. By using one arm less, the console surgeon sometimes may feel incapability at making appropriate retraction of the lung, particularly in station 7 dissection, if the assistance could not provide enough support. Four arm VATS based approach may be a solution to this discomfort.

In VATS based approach, the most important disadvantage is CO_2 insufflation could not be provided due to large access incision opened to room air. The posterior access incision used for upper lobe resections and segmentectomies of the upper lobe could not be converted to a useful thoracotomy to overcome a major problem from the upper lobe vessels. This is because the level of thoracotomy would be low in this situation. When there is a need for an open conversion, another thoracotomy from anterior is recommended.

Discussion

Briefly, the specific robotic techniques utilized are as follows: completely portal four arm technique (1); a completely portal three-arm technique with 5 cm extraction incision (7); and a three- or four-arm technique with a 3 cm to 4 cm non-rib spreading utility incision (3). VATS based approach is consistent with the 3–4 arm technique with a non-rib spreading utility incision. In VATS based approach a utility incision is created to help in retraction, suction and dissection by the table surgeon. This access port is also used to extract the large specimen out. In this surgery, since there is a communication with the intrathoracic cavity and the operating room environment, the benefits of CO_2 insufflation could not be used. The second platform is the completely portal robotic lobectomy (CPRL) which allows entire procedure through the ports. Thus, definitely CO_2 insufflation is allowed and helpful in this situation. The specimen is extracted by enlarging the most inferior port.

The comparison of both techniques could be seen in *Table 1*. Both types of platforms have similar perioperative

Table 2 Outcome differences between VATS based and CPRL operations

Author	Number of patients	Duration of surgery	Conversion rate (%)	Morbidity/ mortality rate	Stay	Platform used
Louie *et al.* (7)	46	213	NA	17/0	4	VATS based
Gharagozloo *et al.* (8)	100	240	0	21/5	4	VATS based
Melfi *et al.* (9)	23	192	9	39/4	5	VATS based
Veronesi *et al.* (10)	91	239	11	NA/0	5	VATS based
Veronesi *et al.* (3)	61	235	13	20/0	4.5	VATS based
Park *et al.* (11)	325	206	8	25/0.3	5	VATS based
Dylewski *et al.* (12)	200	90	3	26/2	3	CPRL
Cerfolio *et al.* (1)	168	132	7.7	28/0	2	CPRL
Melfi *et al.* (13)[a]	69/160	222/166	10/6	NA/0; NA/0	3.8	VATS based/CPRL
Nasir *et al.* (14)	394	107	10	27/0.25	2	CPRL

[a], two groups compared [standard da Vinci Surgical System (Intuitive Surgical, Sunnyvale, CA, USA) *vs.* da Vinci Surgical S/Si systems]. VATS, video-assisted thoracic surgery; CPRL, completely portal robotic lobectomy.

outcomes. The outcomes are compared in *Table 2*. According to authors, outcomes are not different in both approaches. Routine use could be recommended based on the surgeon's and center's preferences.

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Footnote

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Robotic sleeve lobectomy: technical details and early results

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Introduction

Sleeve lobectomy as described in other parts of this journal's special edition avoids the morbidity of the resection of another lobe of the lung. More importantly, it often avoids the vastly increased morbidity of pneumonectomy. There are few reports of sleeve lobectomy performed via minimally invasive techniques. Zhou and colleagues in 2015 reported on 10 patients (1) and showed that sleeve lobectomy can be performed safely with similar early and late outcomes compared to a sleeve lobectomy performed via thoracotomy. We are aware of no published reports of robotic sleeve lobectomy except for a few case reports, yet we know several surgeons who have performed a handful safely. This chapter we will focus on the specific technical aspects of robotic sleeve resections of the airway and also briefly outline our early results in 8 patients which maybe the largest series of robotic sleeves.

Detailed technical port placement

We prefer the completely portal robotic lobectomy using four arms (CPRS-4) as we have previously described (2,3).

Since the most common sleeve is a right-sided right upper lobectomy we will describe it and on the most common robotic system a daVinci Si (Intuitive Surgical, Sunnyvale ca., USA).

Operative details

If mediastinoscopy is to be performed it is important to do it no more than 1 or 2 days before the definitive sleeve or at the same time and rely on frozen section analysis. This allows for decreasing tension on the anastomosis, by freeing up the left and main stem bronchus and ensuring there is neither N2 nor N3 metastatic disease.

The right pleural space is entered over the top of the 8^{th} rib for sleeve lobectomy of the upper and middle lobes. We enter the pleural space using a 5-mm port exactly 21 cm from the spinous process in the right chest and 23 cm from the spinous process in the left chest. This serves as the camera port.

To initiate the operation we use a 5-mm VATS camera, but this is eventually replaced by a 12-mm robotic zero-degree camera. We only use a 0-degree camera because we believe it reduces injury to the intercostal nerve by having less torque than a 30-degree down camera and importantly it provides significantly more room for the bedside assistant.

A 5-mm VATS camera is used to ensure entry into the pleural space via the camera port as shown in the diagram below. Warmed humidified CO_2 is then insufflated in the chest to drive the diaphragm inferiorly. Under direct vision, a paravertebral block from ribs 3 to 11 is performed using bupivicaine with epinephrine. The next port placed is the most posterior port, which is the site of robotic arm 3. The location for this port is identified by using a long 21-gauge needle through which the bupivacaine is administered. The location chosen is at least two ribs below the major fissure and as far posterior in the chest as possible, just anterior to the spinal processes of the vertebral body. A small 5-mm incision is made and a 5-mm reusable metal da Vinci trocar is placed. This will serve as robotic arm 3.

Robotic arm two is placed next. It is located 10 cm anteriorly to the most posterior incision and along the same rib (most commonly rib 8 for upper lobe segmentectomy and rib 9 for lower lobes segmentectomy). An 8-mm metal reusable da Vinci trocar is used. Recently we have switched to a 5-mm trocar here to reduce pain. Robotic arm 2 is docked to this trocar.

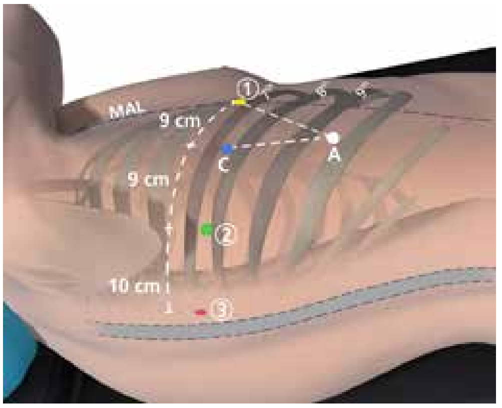

Figure 1 This is a depiction of port placement for a completely portal robotic segmentectomy and/or lobectomy with 4 robotic arms. The circled numbers represent the robotic arms, C indicates the camera port, and A indicates the 15 mm access port. MAL, midaxillary line.

The last two incisions are carefully planned with pen marks on the skin prior to making them. The VATS camera is now placed via robotic arm 2's port in order to see the seeking needle that helps guides these port placements. The location for robotic arm 1 is at least 9 cm anteriorly to the camera port. It should be as inferior and anteriorly in the chest as possible. It is usually much further away from the camera than 9 cm. It is commonly placed along the same rib as the previously placed ports, as shown in *Figure 1*, but can be placed a rib or two higher if needed. It should be located to maximize the depth and width of the triangle made by the camera port, the access port and robotic arm 1. Prior to placing the access port, we ensure that the CO_2 insufflation is active, to depress the diaphragm as low as possible. Once these two port locations are chosen a 12-mm plastic disposable port is placed in the access port and an 8-mm metal robotic reusable port is placed for robotic arm 1.

The robot is driven over the patient's shoulder on a 15-degree angle and attached to the four ports. In general, only four robotic instruments are used for the lobectomy and we add tow more for sleeve resection: a 5-mm lung grasper in robotic arm 3, a 5-mm Schertel in robotic arm 2 (if an 8-mm trocar is used then a Cadiere forceps is used), a 12-mm zero degree camera in the camera port and an 8-mm bipolar curved tip dissector in robotic arm 1. For the anastomosis we use the small robotic needle driver and the robotic Debakey forceps.

Operative technique

After the pleural surface is inspected to confirm the absence of metastases, we proceed with mediastinal lymph node dissection:

Right-sided right upper lobectomy sleeve resection

The inferior pulmonary ligament is divided and lymph node station 9 is removed followed by lymph nodes from station 8 and then 7. Robotic arm 3 is used to retract the lower lobe medially and anteriorly in order to remove lymph nodes from station 7. Care is taken to control the two feeding arteries to the subcarinal lymph node. For a sleeve of the right upper lobectomy the triangle between the bronchus intermedius (BI) and the right upper lobe bronchus is identified. The number 11 lymph node is removed and the posterior segmental artery to the right upper lobe is identified. This can be taken with a vascular stapler now. Robotic arm 3 is then used to retract the upper lobe inferiorly while robotic arms 1 and 2 are used to dissect out stations 2R and 4R, clearing the space between the SVC anteriorly and the azygos vein. We prefer to ligate the azygous on sleeve resection and it can be taken now. The 10R lymph node between the right main stem bronchus and the pulmonary artery is then removed. The appropriate inter-lobar lymph nodes are removed especially the ones that are adjacent to the bronchus to be removed.

Once the posterior segmental artery is stapled or clipped and divided the RUL bronchus can be dissected. If the tumor in the airway prevents this move then the lung should be retracted posteriorly and the anterior hilum viewed.

The right superior pulmonary vein (sparing the right middle lobe vein) and the anterior apical pulmonary arterial branch are identified, encircled and stapled and divided. The rest of the pulmonary artery should be carefully inspected to ensure there are no other small PA braches left going to the RUL.

The fissure is then stapled next and the bronchus is cut last. We prefer to staple the fissure from the back to the front and not in the more traditionally manner from anterior to posterior.

If needed a bronchoscope can be inserted to help mark the best part for the bronchotomy. Perhaps one of the greatest advantages of the robot is the 10 times magnified 3 dimensional view of the operative field. For this reason we prefer to cut the BI first to be able to then look inside the airway to see the optimal location to cut the right main stem bronchus to obtain a negative margin but leave as much of the right mains stem as possible. If the tumor is large and bulky we often will cut the right upper lobe bronchus flush

Figure 2 Robotic right upper lobe sleeve lobectomy for a 72-year-old patient (4).
Available online: http://www.asvide.com/articles/820

at its origin, which allows us to remove the specimen and obtain more room in the operative field.

Preparing for the anastomosis

The ideal instrument used to cut the bronchus is a monopolar shears scissors. We prefer to cut the BI margin first as described above and then the right main stem margin. Separate margins are sent to ensure they are both negative on frozen section but we do not wait for pathology if they appear normal on visualization using the 10 magnified view. We start the anastomoses while the pathologists are cutting and freeze it. It's important to ensure that the distal BI does not twist. An important technique that we have used to avoid any twisting is to place a suture in the BI and cartilage at the 12 o'clock position. We then retract the BI posteriorly and use blunt dissection to obtain more lengthens as we dissect it off of the main pulmonary artery going to the middle and lower lobes. This is a nice maneuver that affords length of the BI in the same way that mediastinoscopy affords length of the right and left main stem and trachea. It is critical to keep the posterior part of the airway (both the right main stem and the BI) posteriorly so they stay aligned. It should run parallel to the vertebral bodies

As shown in the video (*Figure 2*). We then lift up the stapled and divided azygous vein and retract it posteriorly and then dissect out the tissue off the membranous mainstream part of the trachea. In addition, we remove all of the subcarinal lymph node to clearly see the right left main stem. This provides length and reduces tension on the anastomosis.

The anastomosis

We use the small robotic needle driver with which has a scissors in its heal to cut after tying. We prefer 3-0 Vicrly suture on an RV 1 needle that is cut to be 8 cm in length. The first suture is critical and the knot should be outside the airway. We preferred to place our first suture at 6 o'clock on the right main stem bronchus (from out to in) as shown in the video to show on the figure and then from in to out on the BI at the corresponding 12 o'clock. This places the knot in the cartilage close to the membranous part of the airway and tie without tearing the tissue. It is important not to place the first suture in the membranous part of the airway since it can tear as it is tied. We then place interrupted sutures with knots on the outside staying on the cartilage part of the airway to slowly bring the two cut ends together. Although a running suture line is what we prefer for open cases (using 3-0 or 4-0 PDS on an RV 1 needle) the robotic instruments can fray sutures especially earlier in one experience and the PDS is difficult to work with on the robot. For these reasons we prefer multiple interrupted Vicryl's and it allows the resident and fellow to sew and tie. Since the right main stem bronchus has a larger caliber than the BI this is taken into consideration, as the sutures are placed. We do telescope the anastomosis.

Once the entire cartilaginous aspect of the airway anastomosis is completed the lung is then retracted anteriorly and inferiorly, which allows one to view the entire membranous part of the anastomosis as shown below. This can be easily closed with a running PDS or Vicrly suture with knots again outside the airway. The anastomosis can be covered on the right side with the part of the thymus as we have used for over ten years now or the intercostal muscle or pleura can be used. We do not routinely wrap the anastomoses anymore unless there was preoperative radiation and or the patient has risks for a leak such as steroids etc. We do not circumferentially wrap an anastomosis but rather just the anterior aspect of it. Once the anastomosis is completed warm water should be placed in the chest, the CO_2 should be turned off (which is an important step that many seem to forget) and the anesthesiologist is asked to deliver a few small breaths to ensure the anastomosis does not leak. Will use a single 20 French chest tube that is placed anteriorly.

Results

Table 1 shows our results of these eight patients. It

Table 1 Characteristics and early outcomes of patients who were scheduled for a planned robotic sleeve resection

Age/gender	Operation	EBL in CC	#LN's removed	Pathology histology	Length of stay days	Complications	Follow-up bronch performed
61/M	RUL sleeve	30	24 LN's	T2b (6 cm) N0M0 squamous	3	No	3 and 6 months—normal
80/M	RUL sleeve	75	25	T2b (5.5 cm) N0M0 Squamous	4	No	3 and 6 months—normal
68/M	RUL sleeve	45	23	T2b (5.3 cm) N0M0 squamous	3	No	3 and 6 months—normal
55/M	LUL sleeve	100	27	T2a (4 cm) N2(5)M0 squamous	4	A fib	3 and 6 months—normal
54/F	RUL sleeve	35	19	T2a (3.7 cm) N1M0 squamous	4	No	3 and 6 months— normal
48/M	RUL sleeve	20	21	T2a (3.2 cm) N0M0 neuroendocrine	3	No	3 and 6 months—normal
8/F	Sleeve resection of BI	10	19	T2a (4.5 cm) N0M0 neuroendocrine	1	No	3 months—normal
79/M	RUL sleeve	30	23	T2b (5.8 cm) N1M0 squamous	3	No	3 and 6 months—normal

#, the number. BI, bronchus intermedius.

shows that six had a right upper lobectomy, one had left upper lobectomy sleeve and one had a resection of a neuroendocrine tumor of the BI. There was one conversion to thoracotomy for bleeding that occurred in an attempted right upper lobectomy sleeve because of injury to the apical segment of the pulmonary artery. The artery was adherent to the bronchus. The injury was packed and elective conversion to thoracotomy was performed without the need for blood transfusion. The patient did well and underwent right upper lobe sleeve resection.

There were no 30 or 90-day mortality and no major morbidity. One patient had a short burst of atrial fibrillation for 3 hours. All patients except one are at least 6 months out with no evidence of recurrence on CT scan. All patients have had at least one post-operative surveillance bronchoscopy and there is no significant stricture or recurrent cancer at the anastomosis.

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Thoracoscopic or robotic surgery? No matter, as long as they have good results

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Despite the encouraging results, minimally invasive thoracic surgery is still used in a minority of non-small cell lung cancer (NSCLC) patients, currently in about one third of all major pulmonary resections (1). Since the 1990s video-assisted thoracic surgery (VATS) has gradually become more and more popular and, over the past two decades, it has been gradually accepted as an alternative option to open thoracotomy for selected patients. Compared with thoracotomy, VATS lobectomy is associated with less pain, shorter chest tube duration, fewer cardiac complications (especially atrial fibrillation), lower rate of infectious complications (i.e., pneumonia), lower incidence of blood transfusion, shorter length of hospitalization and faster recovery (2-4). Another significant advantage of VATS has been reported in high risk patients, particularly in those with preoperative poor pulmonary function (5). It has been also argued that the lower impact on the immunity system with reduction of cytokines relapse during minimally invasive thoracic surgery may avoid postoperative immunosuppression, consequently decreasing the risk of complications (6). However, some authors raise concerns about oncologic results, reporting that VATS approach may prejudice oncologic principles of anatomic resection. A retrospective analysis of The Society of Thoracic Surgeons—General Thoracic Database by Boffa *et al*. reported a lack of the completeness of the surgical lymph node evaluation of peribronchial and hilar lymph node dissection by VATS in the decade 2001–2010 (7). However, this study contradicts numerous studies that have showed that open and VATS approaches result in a similar number of sampled lymph nodes. A further previous concern, according to Mathisen, was that to be the gold standard treatment for patients with early stage NSCLC VATS lobectomy should be broadly applicable and not the domain of few experts (8). The spread of dedicated teaching programs of this technique carried out by scientific societies, teaching hospitals and academia, should have passed this concern.

Since early 2000s robotic lung lobectomy had been increasingly reported as a feasible and safe technique in single center series (9-12); however, its widespread adoption remained controversial and the so called robotic-assisted thoracic surgery (RATS) is currently ten-fold less performed than VATS (13). Questions have been raised regarding the safety of robotic techniques when compared with VATS or open lobectomy, and a recent national study showed that the robotic approach was associated with a higher rate of intraoperative vessel injury when compared with VATS (14).

Importantly, according to the robotic surgeons, compared with thoracoscopic approach RATS may provide a more precise control and maneuverability of the instruments both through the three-dimensional view, with an increased depth, and by the wrist-like movement and rotation (9). However, these advantages are significant when operating into the mediastinum, but relatively useful in lung lobectomy where the surgical field is generally wide.

Furthermore, RATS efficacy as a cancer operation should not be questioned. In 302 patients Wilson *et al.* reported that compared with VATS the robotic approach improved pathologic nodal upstaging, which is considered a surrogate for completeness of nodal evaluation and of quality of surgery (15). However, limitation in the use of robotic technology may be associated with the still significant impact on costs (16). Robotic lobectomy had higher related costs than VATS, primarily attributed to the dedicated instrumentation, operative time and personnel (17). This issue is likely the most important barrier to an increased use of this technique especially in public national health care systems.

Finally, it is debatable if proficient thoracoscopic surgeons should invest time and resources to learn the robotic approach, because they are already practicing an effective minimally invasive technique.

In patients with early stage lung cancer the use of robotics could be a viable alternative to the VATS if the above concerns are clearly exceeded with at least equivalent results to VATS in terms of perioperative complications, oncologic outcomes and costs.

In lung cancer patients the keys of the success are early diagnosis and radical resection of cancer to obtain the long-term survival outcome. These keys highlight the importance of looking at the long-term benefit of patient life expectancy rather than at the short-term benefits of a treatment when reviewing and interpreting comparisons of different surgical techniques.

From a methodological point of view, confirmation of the oncologic effectiveness of minimally invasive surgery would be best demonstrated by a large, prospective, randomized series, which will not be forthcoming (18). Although not randomized, the registry design may allow comparisons of important variables in appropriately matched patients, as stated by D'Amico ten years ago (18).

In the 2000s several scientific societies started to develop databases and registries of lung cancer surgery that are currently precious source of data and benchmark for the future. We must be cautioned, however, about the analysis due to possible relevant bias as the retrospective nature of the vast majority of these datasets. Also the selection bias may have a relevant role in misinterpreting the results of these studies.

The registry design method has been adopted in studies comparing minimally invasive approaches to open lobectomy. Yang *et al.* used the population-based National Cancer Data Base, which includes oncologic and survival data from a range of academic and community centers across the United States. The purpose of this study was to measure and compare perioperative outcomes, nodal evaluation, and short-term survival between open and minimally invasive surgery (VATS and robotic) lobectomy and between VATS and robotic lobectomy for clinical T1-2, N0, M0 NSCLC from 2010 to 2012 (1). Importantly, the outcomes were evaluated using an intent-to-treat analysis. In this large database VATS and robotic approaches were used respectively in 26% and 7% of all lobectomy cases. Interestingly, the percentage of minimally invasive cases increased over the study period, reflecting the global trend. Propensity-score matching was used to create comparable groups. The VATS group was found to have a higher conversion rate, and slightly more nodes removed when compared with the robotic group. VATS patients did not differ significantly from the robotic ones with regard to 30-day mortality and 2-year survival. With regard to nodal upstaging, there were no differences between open versus minimally invasive surgery and VATS versus robotic approaches. The authors concluded that the data were consistent with high-quality results of both minimally invasive techniques suggesting the need for the broader implementation.

In a recent study Louie and colleagues analyzed The Society of Thoracic Surgeons General Thoracic Surgery Database to assess quality outcomes of VATS and RATS lobectomy performed in the subset of clinical early stage NSCLC prospectively collected patients, over a five-year period [2009–2013] (13). The use of a large national database of general thoracic surgery including contributes from 128 centers is certainly one of the strength of the study, as well the high volume of patients. Another strong point is the standardized prospective collection of data which makes comparison easier to perform. The study results provide evidence that VATS and RATS approaches are equivalent in terms of all measures of quality, including postoperative complications, length of stay, 30-day postoperative mortality, and nodal up-staging. However, it must be underlined that the data are from high quality thoracic services in United States, as shown by the low overall complication rate, by the rare use of blood products intraoperatively and by the infrequent admission to intensive care unit after surgery. Secondly, study exclusion criteria were conversions, induction chemotherapy or radiation therapy and cases from low volume centers (<20 cases/center); the consequent possible selection bias might impact on the generalizability of the results. The authors conclude that robotic approach might be an acceptable alternative to VATS for lobectomy, although with slightly longer intraoperative times. It is still debatable if such a small difference (13 minutes) in the operative time may significantly affect clinical course of the patients and the overall costs of hospitalization.

The conclusions of the study by Louie *et al.* are substantially consistent with the current National Comprehensive Cancer Network (NCCN®) Guidelines that strongly propose minimally invasive surgery (including either VATS or robotic-assisted approach) for lung resection of early stage NSCLC since there is no compromise of standard oncologic and dissection principles of thoracic surgery (19). Nevertheless, the authors recommend prospective studies to define the role of RATS for anatomic lung resections.

The use of robotic approach to perform lobectomy remains of great interest for the thoracic surgical community. While waiting for a further simplification and reduction of costs of robotic surgery, which is currently equivalent to VATS, we should guarantee more widely high quality procedures to our patients from an oncologic point of view. Moreover, as already stated by experts (20), we should widely spread the VATS lobectomy technique so that more patients might benefit the advantages of minimally invasive thoracic surgery.

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Footnote

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Acceptance of minimally invasive surgery as a whole will dictate the future of robotic surgery

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Minimally invasive surgery (MIS) for thoracic diseases has proven advantages including decreased postoperative pain and hospital length of stay when compared to thoracotomy, and multiple studies provide data to suggest that MIS is oncologically equivalent to thoracotomy for the treatment of early stage lung cancer. Despite the evidence, thoracotomy remains the more commonly performed procedure with video-assisted thoracic surgery (VATS) being performed in about 30% of lobectomies (1-4). The question remains as to whether robotic or VATS is a superior approach to lobectomy for non-small cell lung cancer (NSCLC). This topic has also been the focus of many previous studies which reveal no clear-cut differences between the two in regards to post-operative outcomes (4-9). What makes the study by Yang *et al*. unique, is the use of propensity matching to differentiate between robotic, VATS, and open approaches to lobectomy (10). More specifically, this is a retrospective review of prospectively collected data from a single institution, Memorial Sloan-Kettering Cancer Center, comparing overall survival, disease-free survival, and perioperative outcomes among propensity matched patients with clinical stage I NSCLC who underwent lobectomy via either robotic surgery, VATS, or thoracotomy.

The cases included were propensity matched within a 3% probability of having a robotic procedure for age, sex, clinical stage, cell differentiation, lung function, and smoking status, yielding a total of 470 unique patients. Significant findings included a shorter hospital length of stay for those who underwent MIS, and specific to the robotic group, a greater number lymph node stations, approximately five, were sampled. These perioperative differences, however, did not translate into improved 5-year overall survival or disease-free survival among the three groups. As expected, older age, current smoking status, clinical stage IB, poor cell differentiation, and reduced DLCO were prognostic factors for recurrence or death. Surgical approach was not a significant factor for recurrence or death upon multivariate analysis. Of note, although the authors point out an increased number of sampled lymph node stations in the robotic procedure, the details of lymph node harvest are not addressed. What one should consider is that the results of lymph node sampling may not be directly related to the capacity of the technique but rather to the effort and expertise of the operating surgeon. This phenomenon has previously been demonstrated. In a study by Boffa *et al*., in clinical stage I primary lung cancers, nodal upstaging from cN0 to pN1 occurred more frequently using an open approach, yet as the use of VATS increased and when cases from VATS-predominant participants were compared to open-predominant participants, upstaging was identical (11). In another study by Medbery *et al*., VATS resulted in a greater number of examined lymph nodes, but nodal upstaging occurred more often with an open approach. When patients underwent surgery at an academic facility, the significant difference in nodal upstaging during open surgery versus VATS was eliminated (2).

We would like commend the authors on this well organized and thorough comparison of the various surgical approaches to early stage lung cancer. Without the ability to conduct randomized controlled trials allocating patients to either robotic, VATS, or thoracotomy for lobectomy, this is the best information that we have to date and may finally solidify the notion that MIS is as efficacious as open surgery. Related to this topic is the use of muscle sparing thoracotomies and enhanced recovery after surgery (ERAS) protocols for lobectomy when MIS is not technically feasible and the positive effects on perioperative outcomes (12). Further research is needed to determine the role of ERAS following open lobectomy.

In conclusion, although minimally invasive techniques for lobectomy are increasing in frequency, they still have not become mainstream. The results of this study provide further evidence that MIS is as oncologically sound as open techniques and highlights the similarities between VATS and robotic surgery. Nonetheless, a true comparison of VATS and robotic surgery is not realistic until MIS is accepted as oncologically equivalent to open cases and robotic technology becomes more readily available.

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Footnote

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Robot-assisted surgery in complex treatment of the pulmonary tuberculosis

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Abstract: Surgery of pulmonary tuberculosis associated with open thoracotomy due to dense pleural and vascular adhesions. These reasons limited the use of video-assisted thoracoscopic surgery (VATS) in these cases. Robotic surgical system aimed to performing successfully minimally invasive operations for pulmonary tuberculosis. This paper showed 3-year experience of one chest center in this area. The results of this work are recommendations that facilitate the implementation of robot-assisted lung resection in complex treatment of pulmonary tuberculosis.

Keywords: Surgical treatment of pulmonary tuberculosis; robot- assisted lobectomy; minimally invasive surgery

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Introduction

Currently, thoracotomy is the standard access to perform lung resections for tuberculosis, despite of the widespread use of the video-assisted thoracoscopic surgery (VATS) technique since 1990 and robot-assisted thoracoscopic surgery (RATS) technique since 2004. VATS therapeutic lung resection for tuberculosis is performed only in a few thoracic centers today. First robot-assisted lobectomy for pulmonary tuberculomas was performed in St. Petersburg State Research Institute of Phthisiopulmonology in 2013 (1). Factors, such as dense adhesions in the pleural cavity and hilar structures, limit the using of minimally invasive approach for patients with pulmonary tuberculosis (2). The purpose of this publication was to show the tips and tricks of robotic operations for pulmonary tuberculosis.

Selection of patients

Elective indications for robotic surgery are the same as for VATS. The duration and quality of the treatment before surgery are important to avoid relapses of the disease. Especially it is crucial in the cases of multi-drug resistant (MDR) and extensively drug-resistant (XDR) tuberculosis. Principles of operations in pulmonary tuberculosis are published in the World Health Organization guidelines, 2014. Thereby, it is necessary to observe the conditions for the surgery: localized forms of tuberculosis, disease-free lung tissue around the resection margins, and acceptable surgical risk of pulmonary resection. The main elective indications for surgery in tuberculosis are persistent cavitary tuberculosis after four to 6 months of supervised anti-tuberculosis chemotherapy, failure of anti-tuberculosis chemotherapy in MDR and XDR tuberculosis-cases, complications and sequelae of the tuberculosis process (3).

The key point of the patient's selection is prediction of pleural adhesions in tuberculosis-cases. This is important when using the DaVinci Si surgical system, as long as it causes features of surgical access.

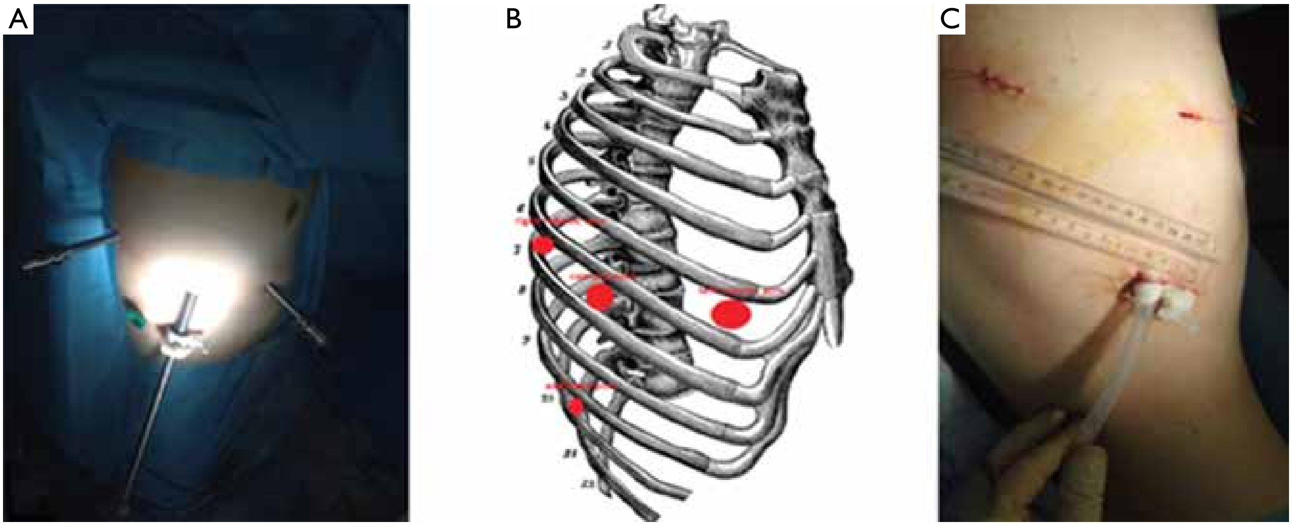

Figure 1 Trocar insertion points for robotic right lung lobectomy: photo (A,C) and scheme (B).

Robot-assisted lobectomy: technique of operation

Different authors proposed VATS based approach (3–4 ports) and total port approach (5 ports) for RATS lobectomy (4,5). Location of instrumental trocars and assistant port were also different. There is no unified technique of the RATS lobectomy today. The use of both methods depends on the surgeon's preference. Some clinics are promoting operation technique with passive assistant. It is 4-arms method usually. We believe that it is sufficient to use three robotic ports performing lobectomy if the assistant is actively working. It gives the operation more dynamic.

We use modified technique of Mark R. Dylewski (4). There are two reasons for modifying the surgical technique: the characteristics of a robotic surgical system Si (it is not possible to divide the adhesions below trocars) and high incidence of pleural adhesions in tuberculosis.

The patient is flexed in the lateral decubitus position. The points of trocars insertion are (*Figure 1*): 1st incision (camera port): 6–7th intercostal space (ICS) at the posterior axillary line, 2nd incision (assistant port): 9–10th ICS, 3rd incision (instrumental port): 5–6th ICS at the anterior axillary line, 4th incision (instrumental port): 7–8th ICS at the scapular line.

The location of assistant port depends on the type of lobectomy. Insertion point of trocar is placed posteriorly for upper lobectomy and anteriorly for lower lobectomy. These differences are depending on the angle needed for introducing of the endo-stapler for dividing pulmonary vein.

One of the difficulties of tuberculosis surgery is the division of pleural adhesions. It is not difficult for robotic surgery, if the adhesions are located at the apex of pleural cavity. However, adhesion under diaphragm is sometimes unavailable for robotic tools (in DaVinci Si version). The first decision of this problem is the lowest port's placement. This feature allows to dividing adhesions up to the port's insertion line (*Figure 2*).

On the other hand, an assistant can divide adhesions into the lower parts of the pleural cavity using VATS techniques (*Figure 3*).

Due to limitations of movements of robotic tools above the diaphragm, once we used repositioning of patient cart of robotic system. We called this method as a re-docking procedure. The standard position of the patient cart is at angle of 15 degrees to the patient's head. The target point for surgical system localized in the apex of pleural cavity in this position. To move the target point above the diaphragm we placed the patient cart at an angle of 175–185 degrees to the patient's head. Camera and assistant ports remain in their places. Left and right instrumental ports were changed between themselves. Robot-assisted thoracoscopic division of adhesions over the diaphragm was more comfortable in this position of the patient cart. After pneumolysis patient cart moved to the original position. This procedure increased the console operative time not more than for 20 minutes.

Steps of robot-assisted lobectomy follow the standard surgical steps of open lobectomy (*Figure 4*). The surgeon performs division of hilar structures using a robotic surgical system. An assistant performs dividing and closing of the

Figure 2 Division of the pleural adhesion with robotic tools (over the diaphragm) (6).
Available online: http://www.asvide.com/articles/1323

Figure 3 Division of the pleural adhesion through an assistant port (over the diaphragm) (7).
Available online: http://www.asvide.com/articles/1324

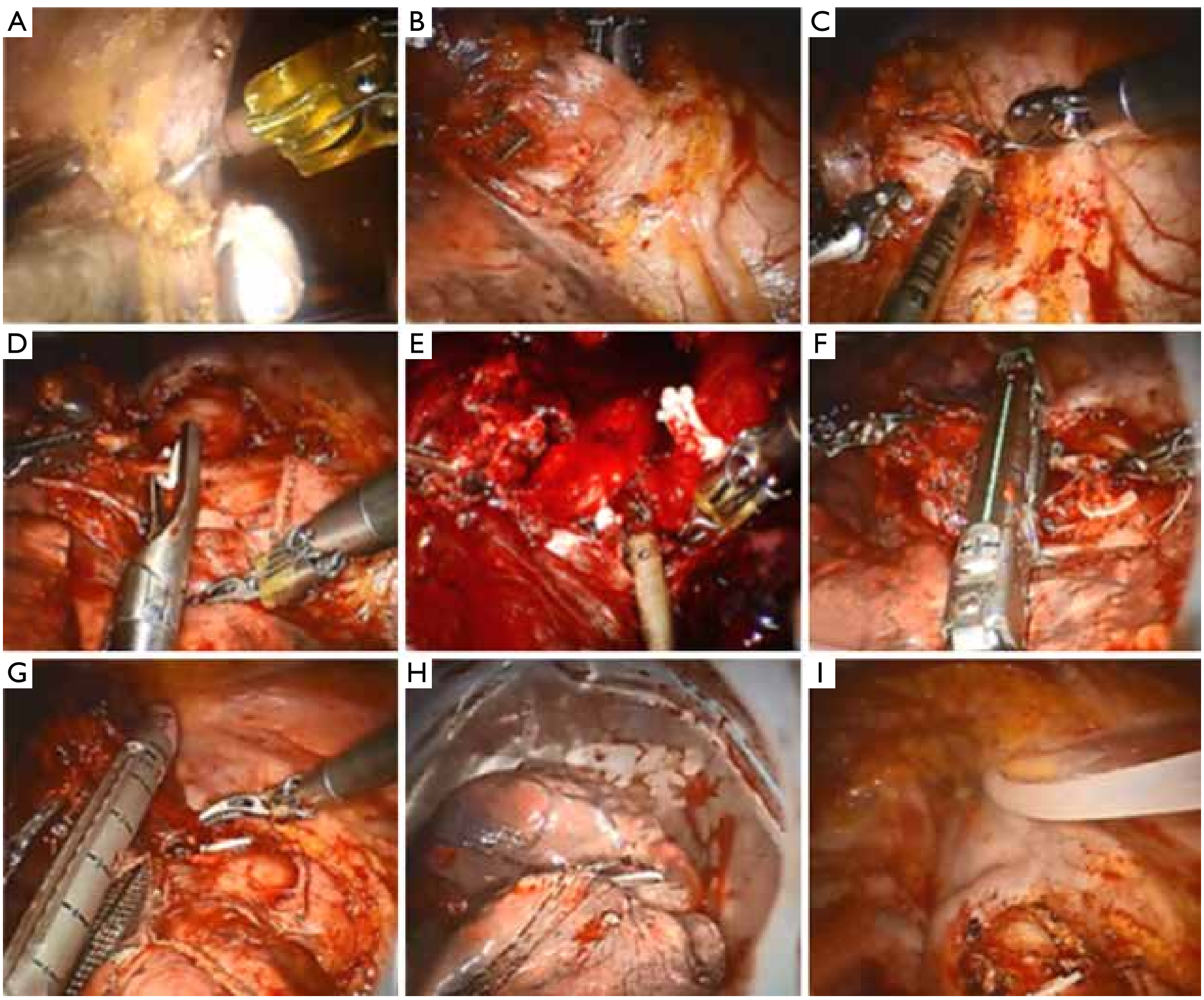

Figure 4 Steps of the right-upper lobectomy: divided of the pleural adhesions (A); dissection of the anterior trunk of the pulmonary artery (B) and vein of the upper lobe (C); dissection and clipping of the posterior segment artery (D), isolation and closing of the bronchus (E,F), division interlobar fissure with stapler (G); removal of resected lobe in plastic bag (H); pleural cavity drainage (I).

Figure 5 Robot-assisted thoracoscopic surgery (RATS) right upper lobectomy (8).
Available online: http://www.asvide.com/articles/1325

Figure 6 Robot-assisted thoracoscopic surgery (RATS) left upper lobectomy (9).
Available online: http://www.asvide.com/articles/1326

Figure 7 Robot-assisted thoracoscopic surgery (RATS) right lower lobectomy (10).
Available online: http://www.asvide.com/articles/1327

hilar structures and lung tissue, removes of the specimen and place the drain under the surgeon's control.

Features of different types of robot-assisted lobectomy

There are many guidelines for the technique of minimally invasive lobectomy today. Nevertheless, there are many different tricks, which make it easier to perform the procedures in every major center. Here are some of them.

Right upper lobectomy: we always use the anterior approach for isolation of the hilar structures (*Figure 5*). At the same time, we usually divide the posterior segment's artery after bronchial step. This is important, since we have had a few cases, when arterial clips were sliding during the isolation bronchus.

Left upper lobectomy: it is inconvenient and much longer to begin fissureless lobectomy with isolation of hilar structures in the interlobar fissure, especially due to gravity of the left upper lobe. Anterior approach provides a good control of the vein and bronchus. Firstly, we identified and divide of the upper pulmonary vein and A1–3 segmental artery. A feature of a bronchial step is carefully isolation of the posterior bronchial wall due to the location of the pulmonary artery (*Figure 6*). There is an excellent visualization of segmental arteries after closing of the bronchus. These arteries could be isolated and clipped separately. However, the dividing of interlobar space is possible with segmental arteries of the upper lobe during this step.

Lower lobectomies. A feature of these operations is the lower port placement than the upper lobectomy. Careful dissection of the oblique interlobar fissure is required for visualization and isolation A6 and basal arteries. In addition, we use stapler with a curved tip at the distal end of the anvil providing enhanced visibility and maneuverability (*Figure 7*).

Right middle lobectomy. This is a rare lobectomy for tuberculosis. This procedure is technically simple in cases with good interlobar fissure. The first step is to visualize and isolation of middle lobe vein. Preliminary separation of lung tissue between segments S5 and S7 considerably facilitates of the isolation of hilar structures (*Figure 8*). Isolation of A4–5 artery in the interlobar fissure is the good decision for cases with dense adhesions in the hilum. Nevertheless, in cases with the absence of interlobar fissures we also use anterior approach and consistently isolate and divide the vein, bronchus and artery.

Figure 8 Robot-assisted thoracoscopic surgery (RATS) right middle lobectomy (11).
Available online: http://www.asvide.com/articles/1328

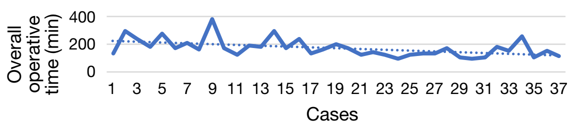

Figure 9 Learning curve of robot-assisted thoracoscopic right upper lobectomy.

Postoperative period

Results of surgery depend on the quality of post-operative treatment of patients with tuberculosis. Treatment protocol of our thoracic center was published in the World Health Organization guideline, and includes proper analgesia, respiratory exercises, daily chest X-rays for the first three days; early, as possible, and removal of chest tubes (3). A key factor of the postoperative treatment is the early prescription of anti- tuberculosis chemotherapy. The bacteriological examination of the specimen is also necessary to determine the degree of the mycobacterium tuberculosis (MTB) drug resistance (3).

Culture-positive patients at the time of surgery must continue the treatment during 6, 18 and 24 months after culture conversion for susceptible, MDR and XDR tuberculosis respectively. These periods might be shorter if the patient has culture-negative sputum at the time of surgery (4 and 8 months for susceptible and MDR and XDR tuberculosis respectively) (3).

Personal experience of RATS lobectomy

Since May 2013, 53 patients with pulmonary tuberculosis were selected for robot-assisted lobectomy (da Vinci Si Robotic System). History of the disease was 28+14 months. Rate of patients with persistent cavitary tuberculosis was 89%. There were 35% of patients with positive sputum smears on MTB despite of the supervised anti-tuberculosis chemotherapy. Mean age of the patients was 38+14 years. The majority of patients were smoking at the time of surgery (18+15 pack/years). Cardiopulmonary function tests showed an adequate pulmonary reserve (forced expiratory volume in 1 second was 3.6+0.97 L). Mean Charlson comorbidity index was 1.3+1.9. All patients had no exacerbation of chronic diseases at the time of surgery.

Most frequent surgery was the right upper lobectomy (37 patients/69%). Learning curve of this operation is shown in *Figure 9*.

Other types of lobectomy were performed with the same frequency (right lower lobectomy—five patients, left upper lobectomy—five patients, left lower lobectomy—four patients).

Forty-eight cases (90%) were associated with pleural adhesions. Total obliteration of pleural cavity was only in three cases (6%). Extrapleural mobilization of lung was performed in seven cases (13%) with subpleural location of the cavity.

There were two cases (4%) with conversion to open surgery. In one case, the procedure was converted to thoracotomy due to dense pleural adhesions in the pulmonary hilum. In another case conversion was accompanied with traction gap of the pulmonary artery between A2 and A6 during divided of interlobar fissure. Bleeding was stopped by pressure. After thoracotomy some stitches of the pulmonary artery was performed to final stop of the bleeding (blood loss was less than 150 mL).

Overall, operative time was 175+64 min and included docking time (17+6 min) and console operative time (109+62 min). Intraoperative blood loss was 82+95 mL (10–500 mL). Postoperative complications were registered by Ottawa Thoracic Morbidity & Mortality Classification System (12). There were 7 (13%) minor and 6 (11%) major complications. Mean duration of air leak was 3±1 postoperative day. Minor complications were mostly associated with small pneumothorax after removal of the chest tube, prolonged air leak, arrhythmia, pleuritis. Severe complications were acute gastrointestinal bleeding treated by endoscopy), hematoma of the right lobe of the liver (required laparotomy), exacerbation of chronic obstructive pulmonary disease (required bronchoscopy), prolonged air leak (required re-insertion of the chest tube) and pleuritis (treated by puncture). About 70% of complications and all serious complications (that

Table 1 Respiratory function during the treatment

The time of examination	Vital capacity (L/%)	Forced expiratory volume in 1 second (L/%)	Forced expiratory volume in 1 second/ forced vital capacity ratio (%)	Diffusing capacity of the lungs for carbon monoxide (%)
Before surgery	3.91/80	2.32/60	63	70
After endobronchial valve installation	4.03/82	3.37/72	65	–
After RATS right upper lobectomy	3.86/75	2.14/52	57	65

RATS, robot-assisted thoracoscopic surgery.

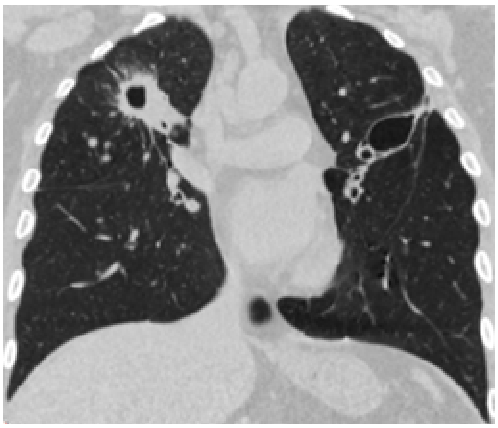

Figure 10 Computed tomography reconstruction of the chest at the time of admission to the chest center.

require reoperation) were during the learning curve.

Mean pain level was three points in first postoperative day and two in fifth postoperative day by visual analogue scale. Analysis of removed lung specimens showed that mean degree of tuberculosis activity was 3±1 by B.M. Ariel score. There were positive smears of MTB in the 79% of specimens.

RATS lobectomy for two-sided pulmonary tuberculosis

Today, surgical treatment of patients with bilateral destructive pulmonary MDR tuberculosis is one of the controversial issues. This clinical case shows our first experience with consecutive robot-assisted thoracoscopic pulmonary lobectomies in combination with therapeutically treatment in such situation.

Male, 22 years old, was admitted in Chest center 24/11/2014. Tuberculosis was diagnosed with a planned X-ray examination in 2010. Initial diagnosis was tuberculosis of the right upper lobe, MTB (–). Primary course of treatment for tuberculosis lasted during 6 months with positivity. Patient was removed from the register.

Relapse of tuberculosis with MDR of MTB was registered in 2014. There was no positivity on the background of anti-tuberculosis treatment based on drug susceptibility test of MTB during 6 months. Nevertheless, there were persistent positive smears on MTB and bilateral destructive cavity in upper lobes of the both lungs. Failure of drug therapy was an indication for surgery.

At admission, the patient had complaints of dyspnea (Modified Medical Research Council Dyspnea Scale—two points). Examinations showed: positive sputum smears on MTB. Spirometry was consistent with moderate chronic obstructive pulmonary disease without exacerbation (*Table 1*). Perfusion scintigraphy showed severe disturbance of blood flow in the lateral section of the upper lobe of the right lung and the middle third of the upper lobe of the left lung. Computed tomography-scans before surgery presented on the *Figure 10* (fibrous cavity in right upper lobe and thin-walled cavity in the left upper lobe). Charlson comorbidity index was one point.

The first stage of treatment (15 December 2014) was installation of endobronchial valve in the left upper lobe bronchus. The procedure was performed without complications. Accordance to A. Levin and coauthors investigation (during 2008–2014 years) endobronchial valve treatment can significantly improve the effectiveness chemotherapy for MDR tuberculosis (13). We chose this method for the left side, because the chance of lobe collapse is higher, when thin wall of the cavity presence, than in cases of fibrous cavity.

The second stage (15 January 2015) was robot-assisted thoracoscopic right upper lobectomy. Overall operation time was 155 min (console time was 120 minutes), blood loss

Figure 11 X-ray examination of the chest after robot-assisted thoracoscopic surgery (RATS) right upper lobectomy. Chest drain.

Figure 12 X-ray examination of the chest after robot-assisted thoracoscopic surgery (RATS) left upper lobectomy. Artificial pneumoperitoneum. Chest drain.

Table 2 Results of morphological and bacteriological examinations of the removed pulmonary lobes

Examination	Right upper lobe	Left upper lobe
Histology form	Destructive pulmonary tuberculosis MTB (–)	Destructive pulmonary tuberculosis. MTB (+)
Degree of tuberculosis activity	4	5
Polymerase chain reaction	DNA of MTB detected	DNA of MTB detected
Microscopy	MTB detected	MTB detected
BACTEC	MTB detected	MTB detected

MTB, mycobacterium tuberculosis.

was minimal. There were no postoperative complications (*Figure 11*). Chest tube was removed on postoperative day 4. Postoperatively, anti-tuberculosis treatment was continued according to drug susceptibility test of MTB.

Six months after the operation (17 August 2015) patient was readmitted to the chest center. There was conversion of the sputum smear on MTB. Nevertheless, polymerase chain reaction test on MTB was positive. Computed tomography scan showed thin-walled cavity in the left upper lobe without any dynamics. Spirometry parameters presented in the *Table 1*.

The third stage of treatment was robot-assisted thoracoscopic left upper lobectomy. Total obliteration of the pleural cavity was found during the installation of the first port. Separation of adhesions started with VATS approach. After that, operation continued with robotic system. Pneumolysis was performed in the intrapleural layer. Overall operation time was 280 min. (console time was 230 minutes), blood loss was 100 mL. Prolonged air leak was in the postoperative period. Artificial pneumoperitoneum was performed 2 times (*Figure 12*). Chest tubes removed on the postoperative day 14. Results of morphological and bacteriological examinations of the removed pulmonary lobes presented in the *Table 2*.

One year after the last operation patient had negative sputum smear on MTB. There were save of the dyspnea at the maintenance level (Modified Medical Research Council Dyspnea Scale—2 points), light sensitivity disorders in the field of postoperative scarring. Computed tomography of the chest showed no progression of the tuberculosis.

Conclusions

Robot-assisted lobectomy demonstrated efficacy and safety in standard lobectomy with pulmonary tuberculosis. Excellent results of robotic surgery allow performing this type of operations at patients with advanced pulmonary tuberculosis lesions. Several features, which were reviewed in this article, can help to perform the robot-assisted operations in the cases of extended adhesions.

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None

Footnote

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

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Pulmonary Surgery

What happens while learning robotic lobectomy for lung cancer?

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Abstract: A surgeon needs to perform a sufficient number of procedures to achieve a level of proficiency. Learning curves demonstrate ongoing improvement in efficiency over the course of a surgeon's carrier. When the surgeon learns the procedure, this means that he has the ability to perform that procedure safely and effectively. The instruction of the da Vinci Surgical System (Initiative Surgical, Sunnyvale, CA, USA) provoked the need for preparing surgeons for complex robotic skills. As low as 5 repetitions are enough to achieve proficiency on basic robotic skills. Robotic-assisted thoracic surgery (RATS) has a steep learning curve compared to video-assisted thoracic surgery (VATS), and it was proposed that 15 to 20 operations are required to establish a learning curve for RATS anatomical pulmonary resections. Based on several studies, one can conclude that after learning, there is a tendency to toward shorter operative times, a decrease in conversion, morbidity and mortality rates, as well as an increase in the number of resected lymph nodes. Our clinical experience on 129 patients undergoing RATS anatomic pulmonary resections over a period of 5-year demonstrated that the learning curve could be established after 14th operation, and the acquired surgical skills and developing experience let surgeon to obtain shorter operative times, operate larger tumors with more advanced stages, have an increased the number of the dissected lymph nodes.

Keywords: Robotic-assisted thoracic surgery (RATS); lung cancer; learning curve; pulmonary resection

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Introduction

The evaluation of proficiency in specific types of operation is a complex and difficult task. It is quite known that if a person is engaged in a repetitive task, his performance improves over time (1). Learning curves for some procedures demonstrate ongoing improvement in efficiency over the course of a surgeon's carrier (2). Learning curve of the robotic-assisted thoracic surgery (RATS) anatomic pulmonary resections have been studied several times (3-7). Besides defining the learning curve, some of these studies briefly investigated the effects of learning on RATS lung cancer surgery.

The aim of this paper is to review the outcomes of learning curve in performing RATS anatomic pulmonary resections for primary lung cancer with regard to patient selection, perioperative events, and postoperative results, and add personal opinions based on our clinical results.

Specific descriptions about learning

A surgeon needs to perform a sufficient number of procedures to achieve a level of proficiency, which is characterized by terms "efficiency" and "consistency". Both terms are the reflections of the developing competence, which comes from performing a sufficient number of procedures independently. Progressing to proficiency necessitates substantial additional operative experience, and requires a qualitative leap in knowledge and performance (8).

A competent surgeon indicates that the surgeon has the ability to perform a procedure safely and effectively. Greater expertise shows that the surgeon has gained additional experience; he knows how to avoid common errors, and has resiliency in case of unexpected events during the operation. Compared to a "competent" surgeon, a "proficient" surgeon will demonstrate efficiency and consistency, in addition to safety and efficacy (9).

Definitions of the learning curve in RATS in general, and in RATS anatomic pulmonary resections for primary lung cancer

There has been an increase in the need for preparing surgeons for complex robotic skills with the instruction of the da Vinci Surgical System (Initiative Surgical, Sunnyvale, CA, USA). Special skills are required to perform robotic-assisted surgery, including EndoWrist instrument manipulation and clutching, 3D visualization of the surgical filed, and camera control; and special training helps to develop and deepen these skills (10). Currently, three robotic training platforms are available: the Robotic Surgical Simulator (Simulated Surgical Systems, Williamsville, NY, USA), the da Vinci Trainer (Mimic Technologies, Seattle, WA, USA), and the da Vinci Surgical Skills Simulator (dVSS, Intuitive Surgical) (11).

Walliczek *et al.* (11) performed a prospective training study using 40 novices who had no experience in endoscopic surgery, to test the effect of training frequency on the learning curve on the dVSS (Intuitive Surgical). Participants performed Match Board, Ring and Rail, and Needle Targeting exercises, with different frequencies over 4 weeks. The authors assumed that total frequency of repetitions of each exercise is crucial for improvement of technical performance. They concluded that five repetitions in a population of robotic novices seemed to be sufficient to achieve the proficiency level. One should remember that this study is based on basic robotic skills, and is not performed in livings (animals or humans).

Video-assisted thoracic surgery (VATS) lobectomy is another minimally invasive approach, and as the same as RATS, it necessitates a number of operation to become competent. Li *et al.* (9) demonstrated that between 100 and 200 cases are required to achieve efficiency, and consistency requires even more cases. Learning curve of VATS thymectomy is also studied. Toker *et al.* (1) used cumulative summation model to evaluate the learning curve for VATS thymectomy, and concluded that a thoracic surgeon could have a high success rate in VATS thymectomy after 60 operations.

It is a common proposal that RATS has a steep learning curve compared to VATS, and can be adopted rapidly by surgeons experienced in VATS (12-14). Jang *et al.* (12) concluded that the outcomes of RATS lobectomy in terms of operative times, intraoperative blood loss, and length of stay were similar to those with VATS lobectomy when the surgeon had an experience of 2 years in VATS lobectomy. Several authors proposed that 15 to 20 operations are required to establish a learning curve for RATS anatomical pulmonary resections (3-5), however, these suggestions have been made according to researchers' personal preferences.

Contrary to the abovementioned studies, two studies gave a specific description of the learning curve using statististical methods (6,7). Both authors constructed a scatter plot to evaluate the relationship of operative times with the extent of experience, and they defined the overall learning curve as the mean ± SD of the sum of the individual learning curves. On the basis of their use of this method, Meyer *et al.* (6) reported that the learning curve could be completed in 15 operations, whereas in our previous study we proposed that the completion of the RATS learning curve could be established after 14 operations (7).

In addition to a competent surgeon and a cumulative number of the cases, two factors also affect the learning curve of a surgeon. The first one is the selection of ideal candidates for surgery. As suggested by Gharagozloo *et al.* (4), patients with minimal comorbidities, a reasonable body habitus, better pulmonary reserves (FEV1 greater than 1 L), and appropriate disease characteristics, such as clinical T1a tumors improves learning. Administrating RATS to the patients with early-stage non-small cell lung cancer, no previous thoracotomy, no neoadjuvant therapy, a body mass index less than 40 kg/m^2, a lesion diameter less than 5 cm, no requirement for extended or sleeve resection are also other positive points to obtain better results and become competent (5,15).

The second factor is the presence of a dedicated team. The table-assistant must understand the steps of the operation and have manual dexterity necessary to rapidly intervene in case of an emergency situation. The operating surgeon ideally, should remain at the console throughout the operation, have a certain trust to the table surgeon to let him to tie sutures, fire staplers, and assist as needed (15). The anesthesia team must be experienced in the management of double-lumen airway, and prepared to conversion to open approach, if necessary (16). Nurses and scrub technicians should be experienced in the setup of the robot, patient positioning, and instrumentation (15).

Outcomes of learning in RATS anatomic pulmonary resections for primary lung cancer

As the level of proficiency and confidence increased, most authors reported a tendency to toward shorter operative times (4-6), although some others demonstrated similar results (15,17). Conversion rate also decreased with greater experience (5,17). Cao *et al*. (14) showed the importance performing more operations to develop consistency; they showed that lower conversion rates and shorter operating times mostly occurred in specialized center having more than 30 cases.

Velez-Cubian *et al*. (17) concluded that the greater experience had no negative effect on morbidity, but mortality appeared to improve with experience. Contrary to this, Meyer *et al*. (6) showed significant decrease in morbidity. Several authors also demonstrated significant decreases in terms of hospital stay with greater experience (4-6,17). In terms of lymph node dissection, Veronesi *et al*. (5) reported that there were no significant differences comparing early and experienced group of patients.

Clinical experiences in robotic thoracic surgery and outcomes of "learning"

RATS program using da Vinci Robotic System (Intuitive Surgical, Inc., Mountain View, CA, USA) was established at our institution in October 2011. From that date to December 2016, a total of 250 operations have been performed by a single surgeon (A.T.) for pulmonary and mediastinal pathologies. In our previous study, we demonstrated that RATS learning curve could be established after 14 operations (7). We investigated the effects of learning on patient selection, perioperative events, and postoperative results in patients undergoing anatomic pulmonary resection for primary lung cancer (n=129). The first 14 patients were selected as learning period (GI), and the following 115 patients as experienced period (GII).

Both groups were similar in terms of age, gender, lesion location, neoadjuvant treatment, comorbidity rates, and pulmonary reserves. As intraoperative parameters, there were similarities in the conversion to thoracotomy, blood transfusion, and tumor subgroups between the groups. Our study revealed that, with the growing experience the operative times (docking, console, and total) decreased ($P<0.05$), the rate of lobectomy increased (43% *vs*. 72%, $P=0.03$), larger tumors could be resected (23 *vs*. 29 mm, $P=0.04$), and the rate of patients undergoing resection due to non-T1a tumors increased (35% *vs*. 68%, $P=0.02$). There were also significant differences in terms of the dissected lymph nodes. Significantly more lymph nodes (overall, N1-level, and N2-level) were dissected in the GII group ($P<0.05$), though this increase did not significantly affect the upstaging in term of N-status. Finally, both groups were equal regarding to postoperative outcomes, such as length of hospital stay, morbidity and mortality rates.

In short, our clinical experience demonstrated that learning curve has no negative effect on conversion rate, need for blood transfusion, upstaging, or length of stay in RATS. However, the acquired surgical skills and developing experience let us to obtain shorter operative times, operate larger tumors with more advanced stages, have an increased the number of the dissected lymph nodes.

Conclusions

RATS has a steep learning curve compared to VATS, and it was proposed that 15 to 20 operations are required to establish a learning curve for RATS anatomical pulmonary resections. Our clinical experience on 129 patients undergoing RATS anatomic pulmonary resections over a period of 5-year demonstrated that the learning curve could be established after 14th operation. We concluded that learning curve has no negative effect on conversion rate, need for blood transfusion, upstaging, or length of stay in RATS. Our another conclusion was that the developing experience let surgeon to obtain shorter operative times, operate larger tumors with more advanced stages, have an increased the number of the dissected lymph nodes.

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Footnote

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

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Tips and tricks to decrease the duration of operation in robotic surgery for lung cancer

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Abstract: Minimally invasive surgery (MIS) for lung cancer has been associated with decreased perioperative morbidity while maintaining similar long-term survival when compared to open thoracotomy. Robotic thoracic surgery constitutes an evolutionary step in this field, beckoning dramatic advancements both in visualization as well as surgical instrument range of motion and ergonomics. As such, robotic thoracic surgery is growing in adoption worldwide. One of its oft-cited disadvantages, however, is increased operative time, especially for less-experienced surgeons. We describe an assortment of tips and tricks that we conclude can safely reduce robotic operative duration.

Keywords: Lung cancer surgery; minimally invasive surgery (MIS); robotic surgery; operative duration

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Introduction

Minimally invasive surgery (MIS) continues to grow in popularity in virtually all fields of surgery, including in the treatment of lung cancer. Thoracoscopic lobectomy has demonstrated improved perioperative outcomes, decreased pain, and similar long-term survival compared to open thoracotomy for patients with early-stage non-small cell lung cancers (1-3). Robotic-assisted surgery is an evolution of minimally invasive thoracic surgery that is becoming increasingly common (3,4). Its most visible benefits include a dramatic advance in visualization with magnified, high-definition, three-dimensional imaging coupled with upgraded instrument maneuverability, building upon what have often been cited as critical weaknesses of video-assisted thoracoscopic surgery (VATS): limited, two-dimensional visualization along with restricted maneuverability (1,5,6). Moreover, robotic thoracic surgery has been demonstrated to reduce perioperative complications and hospital length of stay with similar effectiveness to open thoracotomy; direct comparisons to VATS, while limited, suggest similar efficacy (6-9).

However, one of the most significant criticisms of robotic surgery, in addition and related to cost, is longer operative time (5,9,10). This is frequently associated with the reportedly steep learning curve that comes with robotic surgery as a consequence of its distinct instrumentation and technique (5,9,10). These are valid considerations, as longer operative durations have been shown to independently increase potential for infectious complications and length of hospital stay (11). Compounding this, cost estimations peg an additional minute of operating room time between $22 and $133 in the United States (12). In addition, long operative times can make it more difficult from practicality and safety standpoints to teach robotic surgery to residents at academic medical centers, and surgeons not confident in their robotic operative technique cannot adequately or responsibly serve as mentors for their trainees (13,14). Nevertheless, these hurdles are neither inherent nor inevitable drawbacks. Rather, they can be minimized not only with increased familiarity with the robotic system

Table 1 The recorded sequential steps of each lobectomy (in order of conduct) and allotted time to be completed

Step[#]	Description	RUL	RML	RLL	LUL	LLL	Allotted time (in min)
1	Mark out ports skin	Same	Same	Same	Same	Same	2
2	Place ports	Same	Same	Same	Same	Same	9
3	Inspect pleura	Same	Same	Same	Same	Same	1
4	Resect inferior pulmonary ligament	Same	Same	Same	Same	Same	2
5	Remove LN 9, 8, 7	Same	Same	Same	Same	Same	7
6	Identify RUL and RLL bronchus posteriorly	Same	Skip this step	Same	Remove 10L LN off PA	Same	5
7	Divide fissure between RUL and RLL	Same	Between RUL and RML	Same	Divide fissure between LUL and LLL	Divide fissure between LUL and LLL	10
8	Remove lymph nodes 2R and 4R	Same	Same	Same	#5, #6	#5, #6	7
9	Retract the lung with robotic arm 3	Same	Same	Same	Same	Same	1
10	Remove 10R LN under azygous vein	Same	Same	Same	11L off PA and LMSB	11L off PA and LMSB	1
11	Identify and dissect PA arterial branches	Same	Same	Same	Same	Same	10
12	Identify and dissect PV	Same	Same	Same	Same	Same	5
13	Encircle PV	Same	Same	Same	Same	Same	2
14	Encircle PA	Same	Same	Same	Same	Same	2
15	Guide stapler under PA branches	Same	Same	Same	Same	Same	1
16	Guide stapler under pulmonary vein	Same	Same	Same	Same	Same	1
17	Encircle bronchus, guide stapler	Same	Same	Same	Same	Same	1
18	Divide remaining fissure	Same	Same	Same	Same	Same	10
19	Bag specimen	Same	Same	Same	Same	Same	3

[#], number. LN, lymph nodes; PA, pulmonary artery; PV, pulmonary vein; LMSB, left main stem bronchus; RMSB, right main stem bronchus; LUL, left upper lobe; LLL, left lower lobe; RUL, right upper lobe; RML, right middle lobe; RLL, right lower lobe. [Reprinted with permission (14)].

but also the adoption of efficient techniques—both preoperatively and intraoperatively—married to an intimate understanding of the relevant anatomy. The objective of this paper is to expound upon such tips and tricks to safely decrease the duration of operation in robotic surgery for lung cancer.

Operative technique tips and tricks

Approach each operation with a well-defined, well-communicated systematic plan

Preoperative planning is pivotal to improving intraoperative efficiency. Since 2010, the year of our first robotic lobectomy, we have developed and refined systematic procedures that optimize patient outcomes while enabling an environment conducive to teaching residents (14). These robotic lobectomy techniques have been arranged as a series of major chronologic steps, defined for each of the five different types of lobectomy, as seen in *Table 1* (14). These steps are identified repeatedly before and during operations, allowing every team member—nurses, anesthesiologists, students, and residents—to be aware of both what is happening and what will happen next. In doing so, our multidisciplinary team can prepare for and,

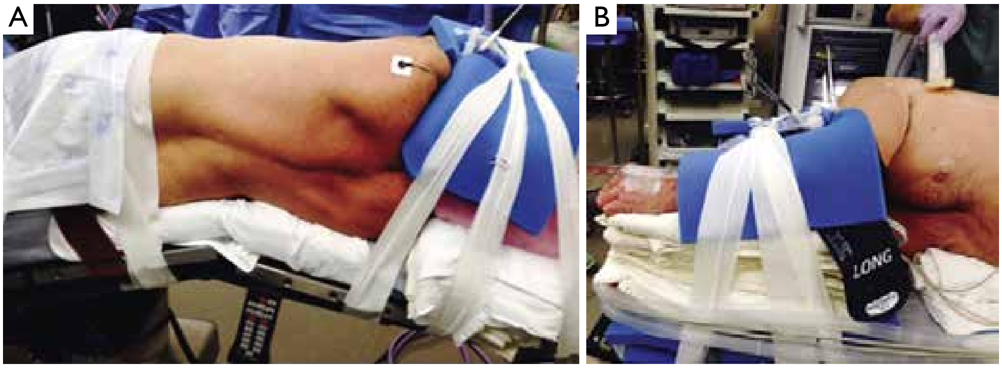

Figure 1 Patient positioning in lateral decubitus with only foam and tape: (A) posterior view; (B) anterior view [Reprinted with permission (16)].

ideally, anticipate next moves, facilitating communication and smoothening transitions between different stages of an operation. For instance, circulating and scrub nurses in our operating rooms have become familiar with when the best time is to procure and ready a stapler for the pulmonary artery, minimizing wasted time between requesting a stapler and deploying it. Thus, it is essential to embrace the obvious and develop and reinforce systematic plans that are shared with and understood by the operative team.

Determine the desired duration of each step in the plan

Dovetailing with the centrality of a systematic plan is the importance of outlining how long each sequential step should take. We have done just that: *Table 1* delineates both the steps to our procedures as well as their respective desired durations (14). These assigned durations were derived from our previous experience as well as videos of other surgeons' robotic operations (14). When adhering to this methodology, operative time can be efficiently but safely minimized and should be under two hours (14). The practice of assessing and analyzing the duration of each step provides twofold benefits. First, by breaking down the steps that are requiring the most time relative to desired duration, areas for improvement can be distinguished and addressed. Second, by keeping track of each operation's progression in real time, surgeons can quickly and quantitatively identify when an operation is likely to take longer than anticipated, and adjust accordingly.

Value stream preoperative protocols

Operating room preincision time is not technically included in the duration of operation and is often left woefully inefficient as a result. However, time in the operating room—whether it is preoperative, intraoperative, or postoperative—is inextricably linked to cost and outcomes. Furthermore, a systematic, optimized approach characterized by value streaming—whereby every action is evaluated as value-added or not—with defined roles can produce dramatic time and cost savings; our protocol decreased preoperative time from 64 to 37 minutes, on average (15).

With this protocol, we have optimized patient positioning with foam pads and tape to ensure adequate anesthesia access without sacrificing surgical maneuverability (*Figure 1*). In so doing, we have phased out the use of axillary rolls, arm boards, and beanbags. Intraoperative central catheter use has been virtually eliminated (75% of cases to 0% of cases) by establishing, in collaboration with anesthesia, criteria to only place one after we are unable to acquire two peripheral intravenous access sites (15). Similarly, intraoperative arterial catheter use has been dramatically reduced (93% of cases to 4% of cases) by largely restricting them to patients who have had coronary artery stenting in the past six months, a recent stroke with unresolved ipsilateral carotid artery stenosis, or post-induction hemodynamic instability (15). Epidural catheter use has also been curtailed (84% of cases to 3% of cases) by transforming pain management to include pre-induction acetaminophen (850 mg) and gabapentin (900 mg) by mouth, intraoperative subpleural paravertebral bupivacaine hydrochloride injections (0.25% with epinephrine), and postoperative acetaminophen, oxycodone, and lidocaine patches (15). Finally, our Foley catheter use has gone from essentially reflexive to selective (99% of cases to 11% of cases) by largely restricting them to patients that regularly

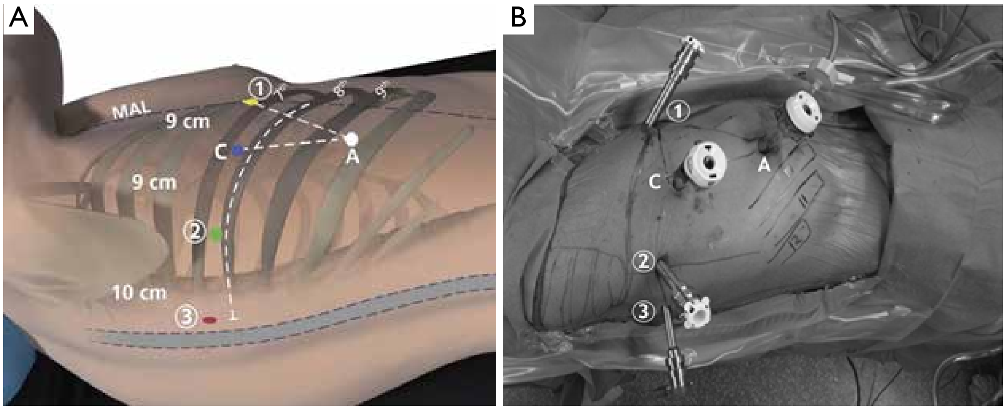

Figure 2 Total port approach with four-port placement for right-sided pulmonary lobectomy with da Vinci Si robotic arms 1, 2, 3, Camera [C], and access port [A] [Reprinted with permission (15)].

have two or more episodes of nocturia (15).

Standardize endotracheal tube placement

Endotracheal tube selection and placement can be optimized for time and outcomes with a defined protocol (15). We first place a single-lumen endotracheal tube in patients who have smoked within the last three months (due to concern for secretions), who have a history of abnormal bronchoscopy, or who have a computed tomography scan indicating what could be an abnormal bronchoscopy. This is done for both diagnostic and therapeutic reasons. Then, a double-lumen endotracheal tube is placed, and is our standard approach for robotic lobectomy. Anesthesiologists who are not experienced with them can struggle with this step; however, we have used a simple and reproducible technique to facilitate rapid and correct placement of the double-lumen tube. The following describes placement of a left-sided double lumen tube (a right-sided tube is generally reserved for a left pneumonectomy or sleeve resection). The patient's trachea is intubated with the tube. A pediatric bronchoscope is inserted into the bronchial lumen and advanced into the left main stem bronchus. The endotracheal tube is then advanced over the pediatric bronchoscope, which effectively acts a guide. The bronchoscope is then inserted into the tracheal lumen to assess the bronchial cuff's location and ensure proper depth of the tube. The tube is then secured with tape.

Optimize port positioning

Positioning of the patient, the operative team, the robotic ports, and the robot itself is a critical yet underappreciated key to efficient operations. Ports are carefully and methodically inserted to maximize maneuverability of robotic instruments, optimize access to the critical structures, and avoid collisions; of note, we attempt to use smaller ports where possible to minimize postoperative pain (*Figure 2*) (16,17). For the da Vinci Si system, we use two 8 mm ports (left and right robotic arm ports), a 12 mm port (camera), and one 5 mm port (fourth robotic arm port); for the Xi system, all the ports are 8 mm ports. We also utilize a 12 mm assistant port that can be used for stapling and exchange of items such as rolled-up sponges and vessel loops. The assistant port is also important in case sudden or catastrophic bleeding occurs. The following is a description of port placement for a right-sided resection.

All ports are marked before making an incision, although slight changes to these locations are often necessary once the intrathoracic anatomy is visualized. The general guideline is that the ports are located in the seventh (upper or middle lobectomy) or eighth (lower lobectomy) intercostal space. The fourth robotic arm is located 2–3 cm from the spine, the left robotic arm port is located 10 cm away from that port, the camera port is located 9 cm from the left robotic arm port, and the right robotic arm is located 9 cm away from the camera port (*Figure 2*). We insert the camera port first and perform an intercostal nerve block from the exterior using the spine as a guide. We then place the fourth robotic arm port, positioning it two ribs beneath the oblique fissure. The camera is then inserted through the fourth robotic arm port and the other two ports are subsequently inserted under direct vision. The

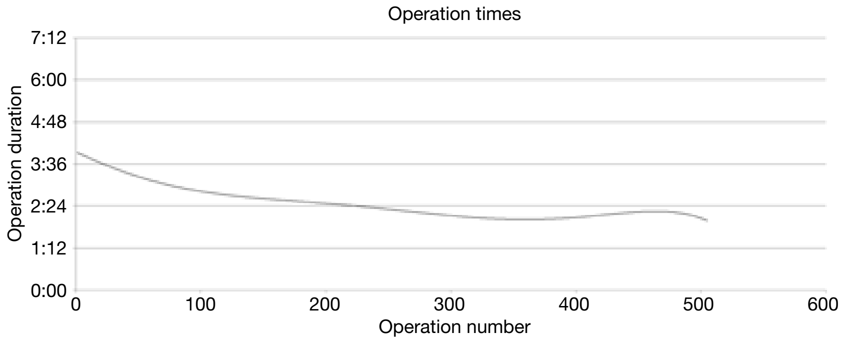

Figure 3 Operative times for robotic lobectomy between February 2010 and December 2015 (n=520) [Reprinted with permission (14)].

assistant port is a 12 mm port and is inserted just superior to the diaphragmatic fibers—and hence as anteroinferior in the chest as possible—while being triangulated between the camera and right robotic arm ports. This isosceles triangle positioning maintains excellent robotic arm maneuverability while securing adequate space for the bedside assistant. For the Si system, the robot itself is subsequently steered at a fifteen-degree angle over the patient's shoulder and then docked. For the Xi system, 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 thirty-degree one due to its decreased torque, which reduces the chances of intercostal nerve injury (16).

Adapt efficient intraoperative processes

It is difficult to quantify how particular technical details can help decrease operating time. However, certain concepts and practices have proved helpful to us as we have refined our technique and safely increased the speed of our lobectomies over time (*Figure 3*) (14).

We perform our mediastinal lymph node dissection first—this ensures a thorough dissection and, especially in the case of level 7 lymph nodes, helps facilitate isolation of hilar structures. We believe that the use of carbon dioxide insufflation saves time by decreasing the size of the lung parenchyma (improving visualization) while also decreasing bleeding secondary to increased intrathoracic pressure. Naturally, optimal retraction of the lung is critical. As in VATS lobectomy, removing lymph nodes prior to encircling structures leads not only to improved lymphadenectomy but helps facilitate the safe isolation and division of vessels and bronchi. We retract vascular structures gently with rubber vessel loops and use a curved tip stapler when encircling them, processes which we believe help facilitate what are generally the most intimidating steps of the lobectomy. Removal of the resected lung is protocolized into steps to avoid clumsy and dangerous handling of specimen removal: (I) place the specimen in the fourth robotic arm and maneuver the arm up and away; (II) position the bag away from hilar structures; (III) pull down on the tip of the bag as it is being deployed to ensure that it opens in the correct direction; (IV) drop the specimen into the bag with the fourth robotic arm; (V) hold the back of the bag with the fourth robotic arm; (VI) use the left and right robotic arms to push the specimen into the bag; and (VII) let go of the bag with the fourth robotic arm and have the assistant close the bag.

Although we have listed the conventional order of steps during robotic lobectomy, it is important to be flexible and recognize the fact that individualized patient anatomy (variations include incomplete versus complete fissure) can dictate a rearrangement of steps to make the operation faster. For instance, isolating and dividing the bronchus first during a right upper lobectomy can make the rest of the operation simpler. Dividing the fissure first, which is often saved for last in VATS lobectomy, can also be helpful in certain situations. We generally do not reinsufflate the lung to "test" it after the bronchus to be resected is clamped, as we believe it is an unnecessary step in most cases.

Discussion

MIS for the treatment of lung cancer continues to grow in popularity for its superior perioperative outcomes as well as comparable long-term survival relative to open thoracotomy for early-stage non-small cell lung cancers (1-3). Within the domain of MIS, robotic surgery represents a frameshift by ameliorating many of the weaknesses that have bedeviled VATS. For this reason, we strongly believe that robotic thoracic surgery represents the future of lung cancer surgery. As it continues to evolve and surgeons grow more experienced with it, operative time and outcomes from robotic surgery will continue to improve, as they have been shown to already (18,19).

In addition to the benefits of familiarity, however, there are a multitude of strategies to reduce operating room and operative times while maintaining or even improving patient safety and outcomes. This is vital, as every minute of wasted time in the operating room is costly and potentially hazardous. We have presented six tips and tricks to this end: (I) develop and communicate a systematic plan of action; (II) determine and track the desired time for each sequential step; (III) utilize value streaming preoperative protocols; (IV) standardize endotracheal tube placement; (V) optimize port positioning; and (VI) adapt efficient intraoperative processes.

The suggestions in this paper draw on our many years of accumulated experience and fine-tuned techniques, which we have published in the literature. Hence, a strength of this paper is that the tips and tricks described have been extensively practiced and optimized, ensuring that they do not sacrifice patient safety or outcomes. The main limitation of this paper is that, by virtue of basing itself on the recorded experience of a single institution, the paper's generalizability cannot be proven. Furthermore, the process of optimizing the efficiency of our operating room and robotic surgery is a continuous one; therefore, it is impossible to individually quantify the benefit of any of these particular interventions. However, we were careful to craft our descriptions so that they can be standardized. We look forward to widespread adoption and subsequent study of these strategies—and other innovations—to further evaluate their respective benefits while identifying ways to improve upon them. This will enable us to realize the full potential of robotic surgery for the treatment of lung cancer.

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Footnote

Conflicts of Interest: O Ramadan: none; B Wei: Medtronic—speaker; RJ Cerfolio: Intuitive Surgical—proctor, speaker, lecturer; Ethicon—speaker, teacher; Community Health Services—consultant; KCL—consultant; Bovie—consultant; C-SATS—consultant.

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Robotic lobectomy and segmentectomy for lung cancer: results and operating technique

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Abstract: Video-assisted thoracic surgery (VATS) is a minimally invasive approach with several advantages over open thoracotomy for the surgery of lung cancer but also some limitations like rigid instruments and suboptimal vision. Robot technology is an evolution of manual videothoracoscopy introduced to overcome these limitations maintaining the advantages related to low invasiveness. More intuitive movements, greater flexibility and high definition three-dimensional vision are advantages of the robotic approach. Different studies demonstrate that robotic lobectomy and segmentectomy are feasible and safe with long term outcome similar to that of open/VATS approaches, however no randomised comparison are available and benefits in terms of quality of life (QOL) and pain need to be demonstrated yet. Several different robotic techniques are currently employed and differ for number of robotic arms (three versus four), the use of CO_2 insufflation, timing of utility incision and the port positioning. The four arms robotic approach with anterior utility incision is the technique described by the authors. Indications to perform robotic lung resections may be more extensive than those of traditional videothoracoscpic approach and includes patients with locally advanced disease after chemotherapy or those requiring anatomical segmentectomy. Learning curve of vats and robotic lung resection is similar. High capital and running costs are the most important disadvantages. Entry of competitor companies should drive down costs.

Keywords: Lung cancer; surgery; robotics; segmentectomy; lobectomy

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Introduction

The paradigm shift—encapsulated by the phrase ‘from maximum tolerated treatment to minimum effective treatment’—that has involved many areas of surgical oncology, has scarcely touched thoracic surgery. Although minimally invasive techniques like video-assisted thoracic surgery (VATS) and robot-assisted surgery, that avoid division of major thoracic muscles and rib-spreading, are available for resecting lung tumours, they are not widely used. A survey conducted by the European Society of Thoracic Surgeons in 2007 found that only around 5% of responding European surgeons were using VATS for pulmonary resections (1). This, notwithstanding the fact that a systematic review of VATS in comparison to thoracotomy for early-stage non-small cell lung cancer (NSCLC)—which included randomized controlled trials—found that VATS was associated with shorter chest tube duration, shorter length of hospital stay, and better survival (at 4 years) than open surgery, all differences being statistically significant (2). Other data show that VATS is associated with reduced postoperative pain, reduced need for blood transfusions and reduced postoperative complications, as well as improved aesthetic and functional outcomes leading to better quality of life (QOL) (3).

The most frequent reason given by surgeons for not using VATS for lobectomy was that it was a difficult technique with a steep learning curve (1).

It would appear that VATS has drawbacks that made its widespread adoption by thoracic surgeons slow. These include counter-intuitive hand movements to manipulate the instruments, an instrument fulcrum effect, and tremor amplification. The surgeon stands over the patient to operate the instruments, while the virtual operating field is displayed on a monitor some distance away, disrupting eye-hand coordination. Furthermore most VATS endoscopes provide low-definition 2-dimensional images with limited magnification possibilities. VATS systems are therefore characterized overall by poor ergonomics, making delicate manoeuvres difficult.

Robotic surgery was introduced at the end of 1990s in part to overcome the limitations of minimally invasive surgery. Probably the first series using a robotic system to perform lung lobectomy was published in 2002 (4). The only currently available robotic systems for performing thoracic surgery are da Vinci Systems produced by Intuitive Surgical, Sunnyvale, California.

The main advantages of robotic technology over VATS are that natural movements of the surgeon's hands and wrists are translated by the computer-assisted robotic arms into precise movements of the surgical instruments inside the patient, with tremor filtration. The surgeon works at a console some distance from the patient and views the operating field in the console monitor, so that the eye-hand-operating field axis is maintained. The endoscope, directly manipulated by the surgeon at the console, feeds variable magnification, high-definition stereoscopic images to the monitor, which may compensate for the absence of haptic feedback (5).

However these are theoretical advantages, and if the trend to less aggressive oncological surgery is also to involve the thorax, then robotic surgery must be shown to be easier than VATS, and produce equivalent or better surgical and oncological outcomes. Furthermore the high capital and running costs of robot systems (6) will need to be reduced, and opportunities for training or retraining thoracic surgeons will need to be expanded.

Robotic lobectomy—published experience

Lobectomy with lymph node dissection is standard of care for stage I and II NSCLC (7). Following the initial reports (4), the feasibility and safety of robotic lung lobectomy was investigated in a series of studies published over in the subsequent 10 years. Park *et al.* (8) reported on 34 cancer lobectomies using a three robotic-arm technique (two thoracoscopic ports and a 4-cm utility incision without rib spreading) in which patient and port positions were similar to those used in VATS, and the surgical steps reproduced those of VATS lobectomy, with anterior-to-posterior hilum isolation. Four patients were converted to thoracotomy. A median of 4 (range, 2-7) lymph node stations was removed. There were no perioperative deaths. Median chest tube duration was 3.0 days (range, 2-12 days), median length of stay was 4.5 days (range, 2-14 days) and median operating time was 218 minutes (range, 155-350 minutes). Gharagozloo *et al.* 2009 (9) reported on 100 consecutive cases operated on with a hybrid two-phase procedure: robotic vascular, hilar and mediastinal dissection, followed by VATS lobectomy. The complication rate was 21% and three patients died postoperatively, considered due to the inclusion of high risk cases. There were no deaths among the last 80 cases, and the first 20 patients were considered to represent the learning phase. The authors considered that the robotic system was best for fine dissection (lymphadenectomy) while the established VATS procedure was superior for the lobectomy phase.

Veronesi *et al.* (5) 2010 presented the first comparison of open muscle-sparing thoracotomy with robotic lobectomy using a four-arm technique and 3-4 cm access port. Propensity scores for preoperative variables were used to match the 54 robotic cases with 54 patients who received open surgery. Hospital stay was shorter in the robotic group, but operating times were longer; however after the first tertile of cases, the duration of surgery reduced significantly. The authors concluded that robotic lobectomy with lymph node dissection was practicable and safe. The mean duration of the robotic lobectomy was around 220 minutes for the initial cases and around 170 minutes during the last phase of the experience (data not presented).

Dylewski *et al.* 2011 (10) reported on 200 lung robotic resections using an approach in which pulmonary resection was performed through the ports only, and pneumothorax was induced by CO_2 insufflation. At the end of the procedure the specimen was extracted via a subcostal trans-diaphragmatic approach, and the diaphragm subsequently repaired. Median duration of surgery was short at 100 minutes (range, 30-279 minutes) and median hospital stay was three days. However, the readmission rate was high (10%) usually for effusion, requiring drainage, or postoperative pneumothorax.

Like Veronesi *et al.* (5) 2010, Cerfolio *et al.* 2011 (11) used a propensity score to match 106 consecutive patients who received robotic lobectomy to 318 patients who received open rib and nerve-sparing lobectomy. The robotic group had numerically lower morbidity and mortality (0%

vs. 3.1%), significantly better mental QOL and significantly shorter hospital stay (2.0 *vs.* 4.0 days). However operating time was significantly longer with the robotic approach (2.2 *vs.* 1.5 hours). During their experience, the authors modified their technique to add a fourth robotic arm, a vessel loop to guide the stapler, CO_2 insufflation, and specimen removal though a supra-diaphragmatic 15 mm access port—changes which reduced operating times and conversions. Cases with larger tumours, hilar node involvement, or previous chemoradiation for nodal involvement were not excluded, amounting to enlarged indications for minimally invasive lung cancer resection. The authors commented that the robot made it possible to perform an "outstanding" node dissection.

Schmid's group in Innsbruck (12) in 2011 compared posterior (first five patients) and anterior robotic techniques in a learning series of 26 patients. Median hospital stay was 11 days (range, 7-53 days), median operating time was 228 min (range, 162-375 min), and one death occurred within 30 days. The group initially favoured the robotic technique, but in a review stated (13) that they had returned to VATS for major lung resection as the clinical advantages of the robotic approach were insufficient to justify the greater expense and longer operating times.

In 2012 Louie *et al.* (14) published a case-control evaluation of 53 consecutive robotic lobectomies or segmentectomies and 35 anatomic VATS resections, with nodal stations sampled in both groups. Although surgical and postoperative outcomes were similar in the two groups, robotic cases had significantly shorter duration of narcotic use and earlier return to normal activities. The authors reported that the two approaches afforded similar possibilities for performing mediastinal lymph node dissection; however robotics gave greater confidence in dissecting hilar lymph nodes.

The publication of Park *et al.* (15) is the only one so far to evaluate long-term oncological outcomes after robotic lobectomy. This study examined 325 consecutive patients who underwent robotic lobectomy for NSCLC at three centres (two in Italy, one in the USA) between 2002 and 2010. Most (76%) cancers were stage I, 18% were stage II, and 6% were stage III. Median follow-up was 27 months. Overall 5-year survival was estimated at 80% [95% confidence interval (CI): 73-88%]: 91% (95% CI: 83-99%) for stage IA, 88% (95% CI: 77-98%) for stage IB, and 49% (95% CI: 24-74%) for stage II. For stage IIIA patients, 3-year survival was 43% (95% CI: 16-69%). These findings suggest that robotic lobectomy for NSCLC affords long-term stage-specific survival consistent with historical results for VATS and thoracotomy.

The number of lymph nodes removed was used as an indirect indicator of oncological radicality in the comparative studies of Veronesi *et al.* (5) and Cerfolio *et al.* (11). Median numbers of lymph nodes removed were indistinguishable in the robotic and open procedures, suggesting that the robotic approach achieves similar oncological radicality to that achieved by thoracotomy. Two other studies (14,16) found no differences in numbers of lymph nodes removed by VATS and robotic lobectomy for lung cancer.

The frequency of nodal metastases identified in clinically node-negative cases is another indirect indicator of oncological radically. The paper by Park *et al.* (15) on 325 robotic lobectomies found that 13% of stage I cases were upstaged to N1. This is similar to upstaging rates reported after open surgery by Boffa *et al.* 2012 (17) and higher than VATS (18) suggesting that robotic surgery may offer better radicality than VATS. Wilson *et al.* (19) retrospectively reviewed patients with clinical stage I NSCLC after robotic lobectomy or segmentectomy at three centres. They found the overall rate of pathologic nodal upstaging of 10.9%, 6.6% for hilar (pN1) upstaging and 4.3% for mediastinal (pN2) upstaging. After comparing their findings to those for VATS and open thoracotomy as reported in recent publications (2,17,18,20) and adjusting for clinical T stage according to the AJCC, 7th edition, the authors concluded that rate of robotic pathologic nodal upstaging for clinical stage I NSCLC was superior to that for VATS and similar to that for thoracotomy.

Park *et al.* (21) reported that the initial capital cost of the da Vinci robot system was about a million USD in 2008, annual maintenance was 100,000 USD, and cost of disposables 730 USD per operation. They estimated that it was about 3,981 USD more expensive to use per operation than VATS. Nevertheless the robotic operation was cheaper than open thoracotomy (by about 4,000 USD), mainly because thoracotomy patients remained in hospital longer.

The costs of using a robotic system for lobectomy and wedge resection were evaluated in a recent study by Swanson *et al.* (22) in which records of 15,502 lung surgery cases from the Premier hospital database were analysed. Only 4% of surgeries were robot assisted and a propensity score was used to create well matched groups for analysis. Using robotic assistance was associated with higher average hospital costs per patient: lobectomy, USD 25,040.70 for robotic *vs.* USD 20,476.60 for VATS (P=0.0001); wedge resection USD 19,592.40 *vs.* USD 16,600.10 (P=0.0001). The study also found that operating times were longer for both lobectomy (robotic 4.49 *vs.* VATS 4.23 hours; P=0.0969) and wedge resection (robotic 3.26 *vs.* VATS 2.86 hours; P=0.0003). Length of stay was similar with no differences in adverse events. Another recent study Nasir *et al.* (23) analysed "approximate financial data" for robotic lung operations performed by one North American surgeon (282 lobectomies, 71 segmentectomies, 41 conversions to open). Median hospital charges were USD 32,000 per patient with hospital profit of USD 4,750 profit per patient. Major morbidity occurred in 9.6%, 30-day operative mortality was 0.25%, and 90-day mortality was 0.5%. And median patient reported pain score was 2/10 at examination 3 weeks after discharge. The authors commented that although these costs were high they were still profitable for the hospital.

Cost analysis of the author experience showed a mean total cost for a robotic lobectomy of around 12.000 euros which is covered by the Italian health reimbursement with no net profit or loss for the hospital.

Robotic lobectomy—technique

Techniques for robotic lobectomy vary. The Milan group uses a four-arm system—three robot arm ports and a utility incision (5). Other authors (4,8) in New York and Pisa started out using three arms, but later adopted a four-arm technique. Dilewski *et al.* (10) and Cerfolio *et al.* (11) use a four-arm technique but making a utility incision only at the end of the procedure because they insufflate the chest cavity with CO_2 to facilitate access. The position of the utility incision (mainly to remove the surgical specimen) varies with surgeon preference. Veronesi and Park use a fourth intercostal space incision, Dylewski *et al.* 2011 (10) use a subcostal 2-4 cm trans-diaphragmatic incision, and Cerfolio *et al.* (11) an incision between ribs 9 and 10 that can be used to extract large tumours. Gharagozloo *et al.* (9) use a hybrid robotic-VATS technique.

Preoperative assessment and indications

Indications for robotic lobectomy do not differ from those for VATS lobectomy. Patients must have adequate cardiopulmonary reserve, and lesions that are resectable by lobectomy or segmentectomy. Some surgeons (10,11) are using robotic lobectomy on patients with advanced lung cancer after induction treatment, lymph node involvement,

Figure 1 Positions of entry ports for right lobectomy with a utility incision in IV or V intercostals space a camera port in VII or VIII i.c. space and two posterior ports for robotic arms. The arrow indicates the direction of entry of the robot cart. The two blue cycles indicate the incisions used for the anterior videothoracoscopic approach with two ports.

and centrally located lesions that require bronchial sleeve resection, which apparently satisfactory results. Standard staging is performed and includes CT with contrast (chest, brain upper, abdomen), and CT/PET (positron emission tomography). For centrally-located lesions bronchoscopy is performed. CT-guided biopsy is performed when a preoperative diagnosis is necessary, for example in patients with co-morbidities, for lesions not highly suspiciousness for cancer, and for centrally located lesions that cannot be removed by (VATS) wedge resection.

Patient positioning and port placement

The patient is positioned in lateral decubitus and single-lung anaesthesia induced via a double lumen endotracheal tube. The robot is positioned slightly behind the patient's head (*Figure 1*).

Using the four-arm technique, three port incisions and a utility incision are made. First entry (if VATS wedge resection not performed, see below) is via a 1 cm incision through the eighth intercostal space at the level of the mid-axillary line, A 30-degree stereoscopic camera is inserted to explore the thoracic cavity and provide visual guidance for

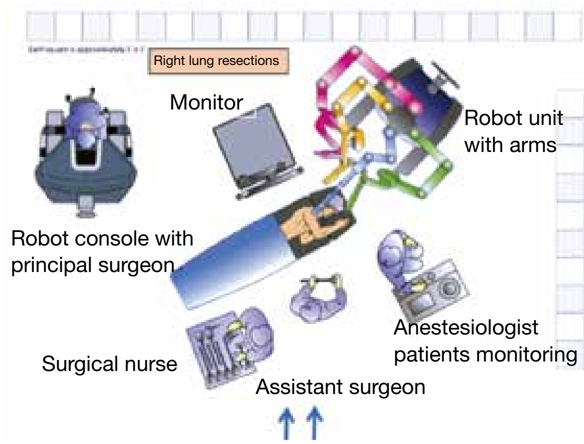

Figure 2 Operating room set-ups for right lung resections.

the successive 3 cm utility incision, which is made through the fourth or fifth intercostal space anteriorly (*Figure 2*). This is followed by an 8-mm incision at the eighth intercostal space in the posterior axillary line for the right robotic arm (on the right side), and another incision in the auscultatory triangle posterior, for the final robotic arm. This fourth incision makes it possible to retract the lung and better expose the operating field.

The ports are standard for all lobectomies except that, on the right side, the camera port through the seventh intercostal space is in the mid axillary line, whereas on the left side this port is moved 2 cm posteriorly (compared to the right) to avoid the heart obscuring vision of hilar structures.

Lesions without a preoperative diagnosis are first excised by standard VATS wedge resection followed by intraoperative frozen section examination.

Small or deep undiagnosed lesions can be located by injecting a solution containing ^{99}Tc-labeled colloid and radio-opaque (iodinated) tracer into the nodule under CT control not more than 24 hours before surgery (24). During surgery a gamma ray-detecting probe is introduced through a port to precisely locate the 'hot' nodule and guide the wedge resection.

The lobectomy commences by isolating hilar elements using a hook or spatula and two Cadière graspers. The hook is manipulated by the right arm of the robot introduced through the utility thoracotomy for right side dissections or through the posterior trocar in the eighth intercostal space for left side lobectomies. One of the Cadière graspers (fourth robotic arm) is used to retract the lung and expose structures. The other grasper is manipulated by the left arm of the robot and used to grip structures during dissection. When a hilar vessel or bronchus is ready to be surrounded with a vessel loop for stapler introduction, a third grasper is introduced (substituting the hook). Vessels and the bronchus are sectioned using mechanical staplers introduced through a thoracoscopic port by the assistant surgeon after removal of a robotic arm. The pulmonary vein is usually the first structure to be isolated and divided. If the lesion is in the right upper lobe, vein resection is followed by isolation of the branches of the pulmonary artery and sectioning, followed by isolation of the bronchus and bronchus sectioning. If the lesion is in the right lower lobe or left lung, after pulmonary vein sectioning, the bronchus is usually isolated and stapled before the artery. When performing middle lobectomy, the most favourable sequence is vein, bronchus and artery.

The incomplete fissure is usually prepared with an Endo GIA Autosuture stapler (Coviden) introduced by the assistant surgeon through one of the ports. The lobe is extracted through the anterior utility thoracotomy in an Endo Catch (Covidien) pouch.

Lymph node dissection

While suspicious lymph nodes are usually removed before lobectomy, radical lymph node dissection is performed after lobectomy using the same technique as in open surgery. Para-tracheal lymph node dissection is performed on the right side without azygos vein division. The mediastinal pleura between the superior vena cava and the azygos vein are incised. The lymph nodes, together with the fatty soft tissue of the region of the Barety space, are removed en bloc using a hook and Cadière grasper. In patients with large quantities of mediastinal fat or very large lymph nodes an UltraCision harmonic scalpel (Ethicon) may be used.

The nodes of the subcarinal station are removed after resection of the pulmonary ligament and retraction of the lung towards the anterior mediastinum to expose the posterior mediastinum. Bronchial arteries can usually be avoided thanks to good visibility, if not they are simply coagulated; a clip is not usually required. Tachoseal is sometimes applied to the fissure surface to reduce air leakage. A single 28 Ch (Tyco Healthcare) pleural drain is positioned at the end of the operation.

Segmentectomy

Anatomic segmentectomy is excision of one or more bronchopulmonary segments, with ligation and division of the bronchi and vessels serving those segments. Usually bronchial, hilar, and mediastinal vascular lymph nodes are examined intraoperatively and only patients with N0 disease receive segmentectomy; others receive lobectomy (25). Segmentectomy and also wedge resection—removal of a small wedge-shaped portion of the lung without intraoperative examination of sampled nodes—have been viewed as mainly suitable for elderly patients or those with impaired lung function, who cannot tolerate lobectomy (26), particularly since the publication of a randomized trial comparing sublobar resection (segmentectomy or wedge resection) with lobectomy in patients with T1-2N0 NSCLC, able to tolerate lobectomy (26,27). After a minimum follow-up of 4.5 years, the trial survival was non-significantly worse, and there were more recurrences (significant) in the sublobar resection arm; however failure seemed to mainly occur in patients who received wedge resection (26,27). By contrast non-randomized studies have reported similar survival rates for segmentectomy and lobectomy (28-30). Furthermore a 2014 meta-analysis (31) which examined overall survival and disease-free survival in patients who underwent sublobar resection and were eligible for lobectomy, found that long-term survival was similar for sublobar resection and lobectomy patients.

Interest in performing segmentectomy has grown since the results of the randomized National Lung Screening Trial (NLST) were published in 2011. This trial, which enrolled 53,000 high-risk North American smokers over 55 years of age, found that mortality was reduced by 20% in the low dose CT-screened arm compared to the arm screened by chest radiography (32).

As result of this study lung cancer screening is becoming more widely adopted (33) and small early-stage lesions cancers will constitute an increasing proportion of lung cancers diagnosed. It is likely that many of these small cancers will be adequately treated by segmentectomy or wedge resection which could ideally be performed using minimally invasive robot-assisted surgery. A number of ongoing trials are now re-examining the role of sub-lobar resection for small early-stage lung cancer.

The Cancer and Lymphoma Group B (CALGB 140503) is conducting a prospective, randomized multi-institutional phase III trial to determine whether sublobar resection is non-inferior, in terms of survival and recurrence, to lobectomy in patients with a small (≤2 cm) single peripheral lesion, confirmed as stage IA NSCLC (34). The trial aims to recruit about 1,300 patients.

Another randomized phase III non-inferiority trial is being conducted in Japan (35). Patients with a single peripheral stage IA NSCLC lesion ≤2 cm are randomized to segmentectomy/wedge resection *vs.* lobectomy. The trial aims to recruit 1,100 patients from 71 institutions over 3 years.

A Milan is co-coordinating an Italian multicentric phase III randomized trial comparing sublobar resection to standard lobectomy. The aim is to recruit 810 patients over 3 years. Eligibility criteria are similar to those of the trials cited above. However there will also be preoperative stratification with CT-PET to identify a subgroup who are PET-negative, have a lesion ≤1 cm, or both. Eligibility criteria are checked intraoperatively and if satisfied patients are randomized. For patients in the PET-negative/≤1 cm subgroup, lymph node sampling is not performed before randomization and if randomized to segmentectomy/wedge resection, receive only lung resection. Patients randomized to lobectomy receive both lobectomy and lymphadenectomy. Patients with nodule >1 cm and positive at PET receive lymph node sampling with preoperative frozen section: only those with a negative frozen section at three lymph node levels and negative margin at resection line are randomized.

Robotic segmentectomy—published experience

Few papers on robotic pulmonary segmentectomy have been published. The first appears to be a multicentric study involving groups in Milan, the Memorial Sloan Kettering Cancer Center, New York, and Hackensack University Medical Center, New Jersey (36,37). The study reported on 17 patients (7 men, 10 women), mean age 68.2 years (range, 32-82 years) who underwent robotic pulmonary segmentectomy from 2008 to 2010. Mean operating time was 189 minutes (range, 138-240 minutes). Median postoperative stay was 5 days (range, 2-14 days). There were no conversions to VATS or thoracotomy and no postoperative deaths. Early postoperative complications consisted of one (5.9%) case of pneumonia and two (11.9%) cases—both with emphysema—of prolonged air leak. Most cancers (64.7%) were in a lower lobe. Median tumour size was 1.11 cm (range, 0.6-2.8 cm) with NSCLC in 8, typical carcinoid in 2, and lung metastases in 7. In three patients the metastases appeared to be from colon cancer, and in one case each were compatible with breast cancer, adenoid carcinoma, gastrointestinal trophoblastic tumour, and osteogenic sarcoma. Six of the primary lung cancers were pN0, and two were pN1. This initial experience was considered encouraging because it offered all the advantages of minimally invasive surgery plus those inherent in the robotic system. In particular, it proved easy to perform radical dissection of the mediastinal and hilar lymph nodes, with no major bleeding, chylothorax or recurrent laryngeal nerve injury. By contrast, lymphadenectomy with VATS can be challenging (38).

The 2014 paper of Toker *et al.* (39) reported on 21 patients (15 with malignant disease) who underwent robotic pulmonary segmentectomy using the da Vinci System. There were no conversions. Four patents had postoperative complications. Mean operating time (at the robotic console) was 84 minutes [standard deviation (SD) 26, range, 40-150 minutes]. Mean duration of chest tube drainage was 3 days (SD 2.1, range, 1-10 days) and mean postoperative hospital stay was 4 days (SD 1.4, range, 2-7 days). The authors removed a mean of 14.3 (range, 2-21) nodes from mediastinal stations, and 8.1 (range, 2-19) nodes from hilar and interlobar stations. They concluded, with the previously cited study, that that robot-assisted thoracoscopic segmentectomy for malignant and benign lesions was practical, safe, and associated with few complications and short postoperative hospitalization. They noted that the number of lymph nodes removed appeared "oncologically acceptable" for early lung cancer patients, and that to evaluate postoperative pain, respiratory function and QOL, a prospective comparison with VATS was necessary.

During robotic segmentectomy, it can be challenging to identify intersegmental planes. A new technique to identify these planes has been recently described (40). After division, within the hilum, of the bronchus, vein, and artery of the target segment, the non-toxic fluorescent dye indocyanine green (ICG) is introduced through the peripheral vein catheter, and the robot visual system is changed to fluorescence mode. Mediastinal and parenchymal tissue appears green 30-40 seconds after infusion. The coloration reaches maximum intensity after about a minute and fades slowly. Thus, perfused lung parenchyma becomes green, while the isolated segment (to be removed) remains uncoloured, affording excellent demarcation of the segment and facilitating transection along intersegmental planes with endoscopic staplers. Since lung palpation is not possible with the robotic technique, the clear view of intersegmental planes that ICG affords makes it easier to ensure adequate distance between the lesion and the resection margin. This procedure has so far been used on few patients but appears promising.

Robotic segmentectomy—technique

Principle of anesthesia, patient position and room set up are similar to those or lobectomy.

The position and number of ports is the same as robotic lobectomy described above, and port placement does not vary with side or type of segmentectomy. The isolation of segmental elements is usually performed using a Cadiere and a hook cautery. The ligation of the vascular branches is either performed with an endovascular stapler or between Hem-o-Lok clips (Teleflex Medical, Research Triangle Park, NC). The parenchima is divided with multiple firings of the endoscopic stapler. Lymph node dissection and postoperative care follow the principles of lobectomy.

Conclusions

Randomised studies comparing vats versus robotic approach are not available so far and few papers describe a long term results after robotic resection for lung cancer. The experiences described in the literature confirm that robotic approach is a good and safe alternative to videothoracoscopic approach, and is considered an easier and more intuitive procedure to afford difficult cases, or anatomical segmentectomy. The improved view and intuitive movements seem to favor an increased radicality in locally advanced disease at mediastinal level.

The paradigm shift—encapsulated by the phrase "from maximum tolerated treatment to minimum effective treatment"—hat has involved many areas of surgical oncology, may now also be widely adopted by thoracic surgeons.

Main limitation of robotic procedures is still represented by higher costs of the technique compared to vats as a single company is on the market thus no competition able to reduce prices is possible.

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Footnote

Conflicts of Interest: I've been proctor in robotic thoracic surgery for Abi medicar.

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Robotic assisted lobectomy for locally advanced lung cancer

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Abstract: Some series report the use of video-assisted thoracic surgery (VATS) in patients with locally advanced non-small cell lung cancer (NSCLC) but, few studies describe the use of the robotic approach specifically for locally advanced disease. One potential advantage of the robotic approach over traditional VATS is the increased radicality. While the benefit of the robotic approach over open thoracotomy is directly related to reduced surgical trauma and the improved tolerability in fragile patients that have received induction treatment. In case of occult N2 disease, robotic assisted surgery can translate into a quicker recovery with improved compliance with adjuvant treatments following surgery. Technical details are reported and described. The robotic instrument technology allows sharp and controlled dissection compared to the typical blunt sweeping methods used in most VATS lobectomy techniques. The authors believe that robotic technology favors a more radical resection in the case of complex locally advanced tumors. Robotic technology has some limitations that have affected adoption such as significant capital and maintenance costs, reduced operating room efficiencies, and a steep learning curve.

Keywords: Lung cancer; locally advanced; robotic surgery; multimodality treatment

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Introduction

Stage III non-small cell lung cancer (NSCLC) represents a heterogeneous group of patients (1) and the treatment of such patients may be a challenge because of their local presentation, requiring extended resection for infiltration of vital mediastinal organs or involvement of loco-regional mediastinal lymph nodes (N2), and the risk of metastatic recurrence (1).

Many advancements in multi-modality managements strategies have occurred in the last decade that has impacted patient operability and overall disease-free survival. Improvements in radiographic staging modalities may be a factor improving outcomes in patients treated with stage III NSCLC in recent studies compared with previous trials. In addition, there have been improvements made in surgery as well as adjuvant and neoadjuvant chemotherapy that clearly has impacted survival; thus, become a standard of care in operable stage III patients (2,3). Lastly, the radiotherapy has gone through revolution in technical advancements that allow for safer integration with chemotherapy and surgery (4). Given the complex nature of patients with stage III NSCLC and the challenging multi-modality approach that is necessary to achieve successful outcomes, treatment for patients with stage III disease should always be organized by a multidisciplinary team (5,6).

Surgical resection remains an integral part of the multi-disciplinary management strategy for selected stage IIIA (N2) patients (7). Despite improvements made in minimally invasive surgical techniques along with the introduction of lung sparing techniques, improved pre- and post-operative care, the use of minimal-invasive surgery still remains uncommon at many centers (8). The robotic approach using the da Vinci system (8-11) represents a technological evolution in the video-assisted surgical approach (12-15). The robotic platform lends itself to several technical advantages such as better view of the operative field (3D instead of 2D), intuitive use of the tools (instruments), precise movement of the instruments and to the many possibilities derived from flexibility and maneuverability of the instruments, which is even superior to that of the human hands (16,17). These improvements can be translated into a greater chance of shortening and simplifying the time of some surgical steps, such as that of the radical lymphadenectomy, bronchial suturing, dissection of hylar lymph nodes from vascular structures. Fore-the-most-part, these advanced skills require years of training and practice when performed with the conventional video-thoracoscopic technique (18,19).

Among the many advantages of minimally invasive surgical approaches over traditional thoracotomy, one is the surgical effect on the immune system (20-22). In particular, the surgical trauma causing an inflammatory condition characterized by the release of pro-inflammatory cytokines and acute phase proteins. Surgical manipulation also exerts a depressing cell-mediated immunity, which is manifested through the alteration in the cell, activation and function of lymphocytes and monocytes. The magnitude of these effects is proportional to the extent of the surgical procedure (21). One possible clinical consequence of the observed immunological changes can be the reported improved overall 4 years survival of patients treated with video-assisted thoracic surgery (VATS) lobectomies compared to thoracotomies (23).

The commonly accepted indications for minimally invasive approach in lung cancers with VATS are localized stage I or II disease (24). Some series report the use of VATS in patients with locally advanced NSCLC (16-19,25,26), but few studies describe the use of the robotic approach specifically for locally advanced disease (27). One potential advantage of the robotic approach over traditional VATS is the increased radicality. While the benefit of the robotic approach over open thoracotomy is directly related to reduced surgical trauma and the improved tolerability in fragile patients that have received induction treatment. In case of occult N2 disease, robotic assisted surgery can translate into a quicker recovery with improved compliance with adjuvant treatments following surgery. In addition, a potential oncological benefit can be obtained with the reduced immune system activation.

The aim of this study is to describe the robotic surgical technique for surgical management of locally advanced lung cancer both before or after induction treatment.

Patient selection and workup

Staging procedure in patients with locally advanced NSCLC included CT with contrast of the brain, chest, and abdomen, total body ^{18}FDG PET-CT. In cases of suspicious N2 disease at imaging endobronchial ultrasound (EBUS) or mediastinoscopy confirmation was usually performed of paratracheal and subcarinal lymph node stations. Patients with a preoperative diagnosis of single station or resectable N2 disease were candidate for preoperative induction treatment with CDDP based chemotherapy for three cycles. The post-treatment staging exams including CT/PET and CT of the brain with contrast. In cases where the disease was deemed resectable, patient was considered a candidate for the robotic surgical approach within 30–45 days from the last chemotherapy. Major contraindications to robotic approach were the intrapericardial pneumonectomy, major vascular resection and reconstruction, atrial resections, extended chest wall resections and masses with the minimum diameter larger than 8–10 cm requiring rib spreading to remove the mass itself.

Preoperative preparation

Preoperative anesthetic evaluation does not differ much from routine evaluation for thoracic surgery. Locally advanced tumors are more prone to involve big vessels or mediastinal structures, therefore preoperative discussion between anesthesiologist and surgeon is mandatory to recognize in advance possible intraoperative problems (bleeding problems, difficult airways managing etc.).

Standard preoperative tests is utilized including: chest X-ray, ECG, blood tests and pulmonary function test (PFT). The use of additional testing for cardiopulmonary evaluation was used on a selective basis.

Anesthesia management

The patient is administer short-acting benzodiazepines (midazolam) following the anesthesiologists assessment and then brought to the operating room. Standard general anesthesia is administered and the airway is secured with and double lumen Carlens endotracheal tube. Careful attention is paid to limiting the total IV fluids to less than 1,000 mL, oxygen level is kept at the lowest level that

Figure 1 Patient position.

allows the patient to maintain saturations in the mid 90% level, and ventilation pressures are stricting observed to avoid barotrauma in the contralateral lung tissue. After positioning and checking double lumen tube, we cannulate two large caliber peripheral veins and place a radial artery monitoring line in the arm contralateral to the operative side. Central intravenous lines are used selectively. If any involvement of central mediastinal vessels is expected, we position a 8.5-french catheter in the femoral vein. Then, we position patient on operatory bed as requested (normally, it's an intermediate lateral decubitus with homolateral arm kept down to easy robot arms working), after we start one lung ventilation and we administer intercostal nerve blocking with L-bupivacaine 0.5% 3 mL/space from T3 to T8. Intraoperative opioids are used, preferring short-acting drugs as remifentanil. Muscle blockade is obtained with rocuronium. Bladder line is positioned.

At the end of surgery, we extubate patients in operating room (OR), then we transfer them in recovery room where we keep them 90–120 min controlling chest X-ray, blood gas analysis, pain, diuresis and adequate drainage tube (blood or air leaking). Pain control after surgery is warranted by opioids and nonsteroidal anti-inflammatory drugs (NSAIDs) [normally we administer for the first 24-hour morphine 20 mg/day and Ketorolac or ketoprofene, paying attentions to postoperative nausea and vomiting (PONV) therapy and gastric protection]. Patients are then transferred to surgery ward.

Equipment preference card

After the intubation, the patient is positioned in lateral decubitus and the dependant portions of the body and arms are padded appropriately (*Figure 1*). The operating table is flexed at the level of the kidney rest. Alternatively, a pillow or a 3-L insufflation bag can be placed under the hip to achieve the same positioning. A four-arm robotic approach is used with Xi or Si Da Vinci system. A utility incision of 3-cm is performed in the 4th intercostal space anteriorly and a skin retractor is placed (Alexis). Under direct vision the 8-mm camera port is introduced in the (the Blue is confusing) 8th intercostal space in the anterior axillary line, two other ports are introduced when possible, along the same intercostal space as the camera port respectively on the line of the tip of the scapula and in the auscultatory triangle (*Figure 2*). Dylewski *et al.* and Cerfolio *et al.* have described alternative techniques for performing the complete portal robotic lobectomy (CPRL) with the use of either three or four robotic port. The technique is a closed chest approach using continuous CO_2 insufflation, with the removal of the specimen performed at the end of the case via a subcostal para-diaphragmatic approach (16,17).

Procedure

Mediastinal exploration and lymph node dissection

The operation begins with a hilar release and radical dissection of lymph node stations.

The preoperative PET/CT provides guidance for nodal station assessment to determine resectability.

The pulmonary ligament is dissected and station R9 lymph nodes are removed, dissection is continued till the inferior pulmonary vein is identified. Explore of the sub-carinal station from the right side, the lung is retracted anteriorly using the tip up instrument introduced in the posterior arm (the 4th). The posterior pleura from the upper part of the inferior vein to the azygos vein along the intermediate bronchus is opened (*Figure 3*). The lymph nodes are removed *en bloc* by dissecting the oesophagus off the sub-carinal area, exposing the right and left main bronchi. Following the bronchus intermedius proximal from the right side the node is freed from the bronchus and dissected off the posterior pericardium is recognised. Care must be taken not to tear the lymph node capsule in order to reduce bothersome bleeding that will slow the pace of the surgery. The bronchial arteries are usually clipped or coagulated using bipolar energy (curved bipolar dissector with the energy source set at 8) (*Figure 4*).

After removal of the nodal specimen, by the bedside assistant through the utility incision, an hemostatic sponge is left in the sub-carinal space.

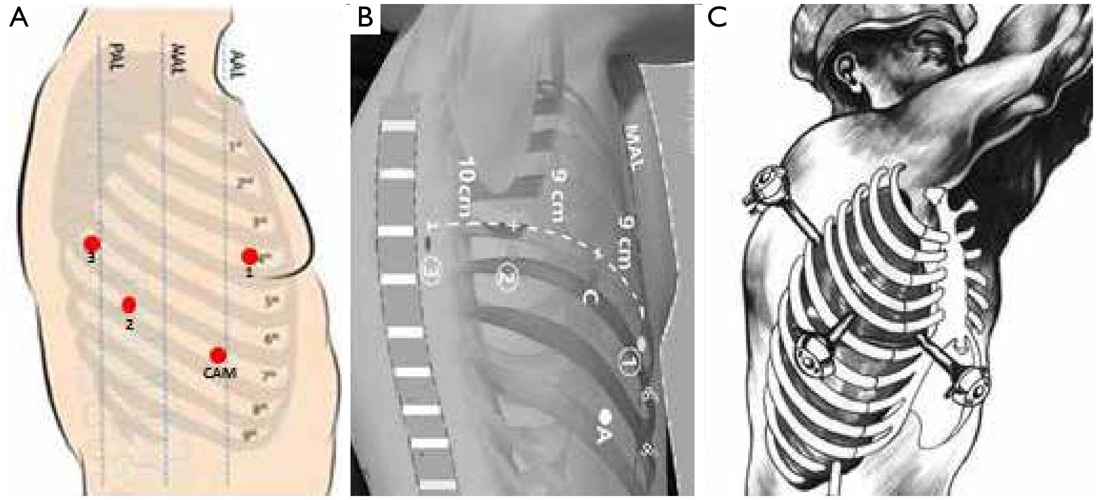

Figure 2 Robotic ports and utility incision.

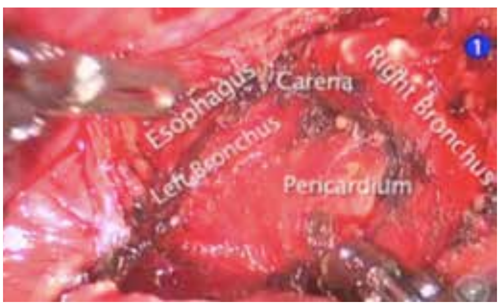

Figure 3 Lymph node dissection of station 7th from the right side.

The lymph node dissection at the level of the paratracheal stations, R2 and R4, and level 3 begins with obtaining exposure by using the tip-up grasper through the 4th arm port to retract the upper lobe inferiorly. The truncus anterior vessel is dissected and the R4 lymph node on the anterior of the vessel is removed. The dissection can be continued underneath the azygous vein to begin removing level 3 nodes. The last step is to dissect above the azygous and between the superior vena cava (SVC) and the anterior margin of the trachea to remove R2 and all level 3 nodes together. In the face of locally advanced disease, large nodes and previous radiation, the authors advise dividing the azygous to assist with exposure (*Figure 5*).

The dissection of the sub-carinal station from the left side is more difficult due to the presence of the descending aorta. In an effort to improve exposure of the sub-carinal space, the use of CO_2 in a closed chest port-only approach

Figure 4 Radical lymph node dissection of subcarinal station form right side (28).
Available online: http://www.asvide.com/articles/1543

Figure 5 Radical lymph node dissection of station R2–R4 (29).
Available online: http://www.asvide.com/articles/1544

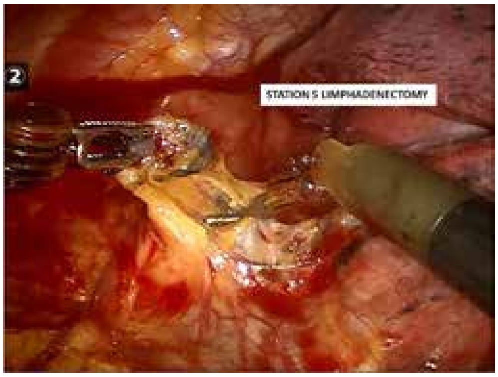

Figure 6 Station 5th and station 6th lymph nodes dissection (left side).

Figure 7 Right lower lobectomy after chemotherapy for N2 paraesophageal lymph node (30).
Available online: http://www.asvide.com/articles/1545

will help. In addition, retraction upward on the left lower lobe bronchus improves exposure especially after dividing the inferior pulmonary vein in a lower lobectomy.

While releasing the tissue along the posterior hilum, the main left pulmonary artery should be exposed and dissection carried distally under the posterior margin of the lung tissue in order to identify the superior segmental and ascending posterior arterial branches. During this process, and the dissection over the suprahilar area, level 5 and level 6 lymph nodes should be removed (*Figure 6*). When removing lymph nodes in the aorto-pulmonary window one should pay attention to sparing the recurrent laryngeal nerve as it traverses under the aortic arch and the phrenic nerve anterior to the superior pulmonary vein. On the right side, the recurrent laryngeal nerve can inadvertently be injured during the supra-hilar lymph node dissection if one carries the dissection too superiorly along the trachea. The phrenic nerve lies anterior to the right superior pulmonary vein similar to the left side phrenic nerve.

Lung resection

Right side

The lobectomy is performed with an anterior to posterior approach to the hilum [robotic-assisted thoracic surgery (RATS) technique described by Park and Veronesi] (8,9) or posterior to anterior approach (CPRT by Dylewski and Cerfolio) (16,17).

The sequence for right upper lobectomy for the RATS technique is vein, arteries (two branches), bronchus and fissure. The traditional endoscopic stapler for vessel transection is introduced through the posterior port after removal of the robotic arm, to avoid a 5th trocar. To complete the fissure staplers are introduced through the anterior utility incision. If the hospital is equipped with robotic staplers the site of introduction is chosen by the surgeon in a more flexible way.

For (RATS) lower lobectomy, the sequence is vein, arteries, posterior fissure and bronchus. Staplers are introduced through the superior anterior utility incision (the same of the right hand robotic arm). The middle lobe sequence is vein, fissure with lower lobe, bronchus and arteries and fissure.

Left side

The (RATS) left upper lobe, the lung is retracted posteriorly by the fourth arm to explore the hilum, the staplers for vessels are introduced through the posterior port after removal of the robotic arm. The sequence of the (RATS) left lower lobectomy is similar to the right lower except the absence of middle lobe bronchus.

Specimen removal

The specimen is usually removed using a plastic bag through the utility incision in the RATS technique or through the para-diaphragmatic incision in case of the CPRL technique.

Right lower lobectomy (Figure 7) (double speed)

The movie shows a right lower lobectomy after chemotherapy for N2 paraesophageal lymph node in a 63-year-old former male smoker. The patient was diagnosed with a right lower adenocarcinoma T1N2 single paraesophageal station, confirmed with endoscopic ultrasound (EUS) needle biopsy and a synchronous left

Figure 8 Left lower lobectomy plus posterior segment of left upper lobe (31).
Available online: http://www.asvide.com/articles/1546

Figure 9 Right upper sleeve lobectomy after chemotherapy for N2 disease (32).
Available online: http://www.asvide.com/articles/1547

lower lobe adenocarcinoma stage clinical T1N0M0. After chemotherapy with partial response of the right lower lobe malignancy, he underwent sequential surgeries that including initially a right lower lobectomy with lymph node dissection followed by a robotic left superior segmentectomy. The postoperative course for this patient was uneventful and he is free of disease after 3 years.

Left lower lobectomy plus posterior segment of left upper lobe (Figure 8)

A 60-year-old smoker was diagnosed with left lower lung lesions with infiltration across the fissure of the posterior segment of the upper lobe with a clinical T3N1M0 stage. He received preoperative induction platinum based chemotherapy and subsequently a robotic left lower lobectomy *en bloc* with posterior segment of the upper lobe and radical lymph node dissection was performed. The challenges of this case were that the lymph nodes within the central hilum were adherent to the artery and difficult to be removed. After completion of posterior fissure and carefully removing the attached lymph nodes, A branch for the posterior segment was isolated and resected between hemo-locks. The parenchima resection was performed including the portion of the left upper lobe involved by the tumor, *en bloc* with the lower lobe. After these steps the case proceeded routinely.

Right upper sleeve lobectomy after chemotherapy for N2 disease (Figure 9)

The patient is a 71-year-old male smoker who presented with a T3N2M0 right upper lobe tumor with large supra-hilar lymph nodes significantly covering the anterior truncus artery. Difficult was encountered achieving exposure and isolation of the origin of the truncus anterior vessel and the right upper lobe bronchus. For that reason, the azygous vein was divided anteriorly and posteriorly to the supra-hilar tumor. After removing the freeing the large level R2 and level 3 nodes from the supra-hilar space, they could not be removed to unroof the truncus anterior artery. Therefore, access to the origin of the truncus anterior was achieved by dividing the right upper lobe bronchus off its origin with endoscissors, Once the right upper lobe bronchus was transected, the origin of the artery was exposed by removing the R10 lymph node anterior to the bronchus. Once the truncus anterior artery is divided, the operation proceeded normally. A right upper lobe bronchoplastic closure of the open upper lobe bronchus was preformed along with a pleural flap.

Post-operative management

At the completion of the procedure: patients are typically extubated in OR and remain in the post-anesthesia care unit (PACU) for 2–4 hours. A chest X-ray, amount of drained liquid, and vital signs are monitored checking. When stable, they are sent to a monitored bed in the surgical ward.

Postoperative pain therapy: elastomer (50 mL volume, 2 mL/h) with morphine 0.4 mg/kg, ketorolac 1.2 mg/kg, ranitidine 150 mg and ondansetron 8 mg. An Acute Pain Service is active in our institution with a double-daily check of patients' pain.

Patients are soon mobilized, 6–8 hours after surgery, if vital parameters are adequate. Twelve hours after surgery they are allowed to eat. Pulmonary rehabilitation starts on post-op day #1. Chest tube drain is removed when the quantity of liquid is lower than 350 mL/24 h and no air leaks are visible.

Tips, tricks and pitfalls

- During lobectomies performed on patients at clinical stage IIIA, where a chemotherapy has already been administered, tissues are usually more fragile than in patients with occult N2 or at the initial stage. In this case, it is important to pay more attention in vascular dissection in order to avoid bleeding.
- The resection of the Barety lodge has to be very accurate in N2 patients. As well as in open surgery, in robotics it is possible to clamp and split the azygos vein, to better expose the lodge and ensure an extended lymphadenectomy.
- In the case in which there is a high diaphragm a stich can be used to stretch the diaphragm down fixing it to the chest wall at level of 10 intercostal space or lower, to expose better the hilum and the mediastinum.
- We recommend to place always in the resected lymph nodes lodge an hemostatic material to compress and fill the empty space to prevent the bleeding and lymphatic leakage.

Conclusions

Stage III NSCLC represent a heterogenous group of patients with pulmonary malignancies. Factors such as large central tumors, multi-station lymph node involvement, T3/T4 involvement, desmoplastic fibrosis and previous irradiate surgical fields make the surgical management of these patients challenging and the outcomes are often variable. Surgery continues to play a central role a select group of stage III NSCLC patients who disease is associated with good prognostic factors. These prognostic factors that predict improved outcomes for surgery patients included limited station mediastinal lymph node disease, response to induction therapy, no comorbidity (33). When patients with stage III NSCLC are found to have good prognostic factors and are consider candidates for surgical resection, a minimally invasive surgical approach has shown to offer favourable outcomes (34). Petersen *et al.* demonstrated reduced complications, length of stay, lower blood loss and decreased mortality. Other authors have shown a positive effect on the immune system correlated to a minimally invasive surgery (MIS) approach (20-22). Robotic approach in this contest can extend the indication of minimally invasive approach in patients with more advanced disease. There have been tremendous advancements made in robotic technology and the platform has certain advantages when surgically treating locally advanced NSCLC. These advantages include, improved mediastinal lymph node dissection, precise control of instruments for dissection for invasive tumours attached to critical structures. The robotic instrument technology allows sharp and controlled dissection compared to the typical blunt sweeping methods used in most VATS lobectomy techniques. The authors believe that robotic technology favors a more radical resection in the case of complex locally advanced tumours. Robotic technology has some limitations that have affected adoption such as significant capital and maintenance costs (35,36), reduced operating room efficiencies, and a steep learning curve (37). For these reasons, the integration of the robotic platform into the management of complex locally advanced disease should be measured and only implemented after proven success on an adequate number of standard lobectomies before approaching more complex situation such as lobectomy after chemotherapy or lobectomy for N2 disease (38).

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Footnote

Conflicts of Interest: G Veronesi is a consultant for ABI Medica SpA and Medtronic. M Dylewski is a clinical educator for Intuitive Surgical and he has received honoraria by Verb Medical, Ethicon and Barb Corp. The other authors have no conflicts of interest to declare.

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Minimally invasive (robotic assisted thoracic surgery and video-assisted thoracic surgery) lobectomy for the treatment of locally advanced non-small cell lung cancer

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Background: Insufficient data exist on the results of minimally invasive surgery (MIS) for locally advanced non-small cell lung cancer (NSCLC) traditionally approached by thoracotomy. The use of telerobotic surgical systems may allow for greater utilization of MIS approaches to locally advanced disease. We will review the existing literature on MIS for locally advanced disease and briefly report on the results of a recent study conducted at our institution.

Methods: We performed a retrospective review of a prospective single institution database to identify patients with clinical stage II and IIIA NSCLC who underwent lobectomy following induction chemotherapy. The patients were classified into two groups (MIS and thoracotomy) and were compared for differences in outcomes and survival.

Results: From January 2002 to December 2013, 428 patients {397 thoracotomy, 31 MIS [17 robotic and 14 video-assisted thoracic surgery (VATS)]} underwent induction chemotherapy followed by lobectomy. The conversion rate in the MIS group was 26% (8/31) The R0 resection rate was similar between the groups (97% for MIS *vs.* 94% for thoracotomy; P=0.71), as was postoperative morbidity (32% for MIS *vs.* 33% for thoracotomy; P=0.99). The median length of hospital stay was shorter in the MIS group (4 *vs.* 5 days; P<0.001). The 3-year overall survival (OS) was 48.3% in the MIS group and 56.6% in the thoracotomy group (P=0.84); the corresponding 3-year DFS were 49.0% and 42.1% (P=0.19).

Conclusions: In appropriately selected patients with NSCLC, MIS approaches to lobectomy following induction therapy are feasible and associated with similar disease-free and OS to those following thoracotomy.

Keywords: Lobectomy; minimally invasive surgery (MIS); thoracotomy; lung cancer surgery

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Introduction

The use of minimally invasive surgery (MIS), including video-assisted thoracic surgery (VATS) (1-6) and robotic lobectomy (7-16) , for the treatment of early-stage non-small cell lung cancer (NSCLC) has increased rapidly. The majority of experience has been in early stage disease, and because of the benefits with respect to hospital stay, morbidity and cost have made MIS a preferred approach over thoracotomy. However, data regarding MIS for the treatment of locally advanced NSCLC, particularly following induction chemotherapy has been limited.

Recently a limited number of case series have been published on the feasibility of the VATS approach for locally advanced NSCLC (17-20). The main focus of these studies was the feasibility of a minimally invasive approach in carefully selected patients. Only one (17) looked at patients that received induction chemotherapy uniformly, although all four studies included some fraction of patients undergoing preoperative therapy. Three of the studies (17-19) did report some survival data that appeared to be consistent with historical comparisons, although only one (19) overtly compared VATS versus open groups. There are currently no published series of robotic surgery for locally advanced disease.

In our institution all three approaches are utilized to treat patients with locally advanced disease. In order to assess the feasibility and survival associated with these approaches, we compared the outcomes of patients who underwent MIS or open lobectomy for locally advanced disease. We considered true locally advanced disease to be those patients with clinical stage II-III disease who underwent induction chemotherapy.

Methods

Patient selection

This study was approved by the Institutional Review Board at Memorial Sloan Kettering Cancer Center (MSKCC). The study was conducted using data from a prospectively maintained database on surgical treatment of NSCLC, covering patients treated between January 2002 and December 2013 at MSKCC.

All patients included in the analysis fit the following criteria: (I) the disease was histologically defined NSCLC; (II) the disease was clinical stage II or stage IIIa by the seventh American Joint Committee on Cancer (AJCC 7) staging system (21); (III) the patient underwent lobectomy; (IV) the resection was preceded by induction chemotherapy or chemoradiotherapy.

We excluded patients with a history of concurrent malignant disease, patients with other previous primary cancers, and patients who had a lung resection procedure other than lobectomy, such as wedge resection, segmentectomy, bilobectomy, pneumonectomy, and chest wall resection. Operative death was defined as death within 30 days of the operation or any time after the operation if the patient did not leave the hospital alive.

Patients were retrospectively classified into two groups on the basis of the surgical approach: MIS group (VATS and robotic lobectomy) and thoracotomy group. Patients undergoing conversion were analyzed by an intent-to-treat analysis and remained in their original group and were not crossed over.

Surgical procedures

At our institution surgeons approached locally advanced disease by thoracotomy, VATS or robotic techniques. Each surgeon that performed MIS (VATS, robotic) conformed to the Cancer and Leukemia Group B (CALGB) 39802-consensus technique of MIS lobectomy (5). The da Vinci Surgical System (Intuitive Surgical, Mountain View, CA, USA) was used to perform robotic lobectomy with either a 3- or 4-arm approach previously described (14). VATS lobectomy was performed via a 4-cm utility incision at the anterior axillary line, at the fourth or fifth intercostal space, without rib spreading. A port at the eighth or seventh intercostal space, at the posterior axillary line, was used for camera visualization, and a posterior port was used for lung retraction and stapler insertion. Thoracotomy lobectomy was performed through a standard, partial muscle-sparing posterolateral incision. Systematic mediastinal lymph nodal dissection or sampling was performed. Conversion was defined as the use of a rib-spreading thoracotomy at any point after initiation of hilar dissection by an MIS approach.

Statistical analysis

Fisher's exact test and the Wilcoxon rank sum test were used to compare patient and disease characteristics, as well as postoperative outcomes, between patients in the MIS and thoracotomy groups. Since the distribution of sex, smoking status, pulmonary function, clinical stage, and tumor cell differentiation were comparable between the two groups (*Table 1*), we did not perform propensity score matching in further analysis. Overall survival (OS) was calculated from the day of surgery to the time of death. Patients who did not die during the study period were censored at the date they were last confirmed to be alive. Disease-free survival (DFS) was calculated from the day of surgery to the date of cancer recurrence or death from any cause. Patients who did not have a recurrence or who did not die during the study

Table 1 Patient and disease characteristics

Variable	MIS (n=31)	Open (n=397)	P
Age, median (range)	67 [50–83]	65 [34–87]	0.038
Sex, n [%]			0.44
Female	14 [45]	215 [54]	
Male	17 [55]	182 [46]	
Smoking, n [%]			0.13
Current	1 [3]	65 [16]	
Former	27 [87]	290 [73]	
Never	3 [10]	42 [11]	
FEV_1[a], median (range)	91 [54–130]	88 [28–141]	0.21
DLCO[a], median (range)	80 [35–114]	74 [30–128]	0.41
ASA score, n [%]			
2	2 [7]	88 [25]	0.069[b]
3	28 [90]	264 [74]	
4	1 [3]	7 [2]	
Pathologic type, n [%]			0.045[c]
Adenocarcinoma	24 [77]	269 [68]	
Squamous cell	6 [19]	77 [19]	
Large cell	0	23 [6]	
Other[d]	1 [3]	9 [2]	
Unclassified NSCLC	0	19 [5]	
Clinical stage, n [%]			0.075
IIA	8 [26]	60 [15]	
IIB	6 [19]	44 [11]	
IIIA	17 [55]	293 [74]	
Tumor site, n [%]			0.99[e]
RUL	9 [29]	183 [46]	
RML	1 [3]	20 [5]	
RLL	4 [13]	56 [14]	
LUL	11 [35]	105 [26]	
LLL	6 [19]	33 [8]	
Cell differentiation, n [%]			0.38[f]
Well	0	10 [3]	
Moderately	5 [16]	112 [28]	
Poorly/undifferentiated	16 [52]	179 [45]	
Unknown	10 [32]	96 [24]	
Induction therapy, n [%]			0.15
Chemotherapy	30 [97]	345 [87]	
Chemoradiotherapy	1 [3]	52 [13]	

Data are no. [%] of patients, unless otherwise noted. DLCO, diffusing capacity of carbon monoxide; FEV_1, forced expiratory volume in 1 second; ASA, American Society of Anesthesiologists; LLL, left lower lobe; LUL, left upper lobe; MIS, minimally invasive surgery; RLL, right lower lobe; RML, right middle lobe; RUL, right upper lobe. [a], percentage predicted; [b], cases with unknown ASA score were excluded; [c], large cell, other, and unclassified NSCLC combined; [d], five cases of adenosquamous cell carcinoma, 2 cases of large cell carcinoma combined with small cell carcinoma, 1 case of adenocarcinoma combined with small cell carcinoma, 1 case of squamous cell carcinoma combined with small cell carcinoma, and 1 case of sarcomatoid carcinoma; [e], tumor site was regrouped into left or right lobe; [f], cases with unknown cell differentiation were excluded.

period were censored at the date they were last confirmed to be alive with no evidence of disease. Both endpoints were estimated using the Kaplan-Meier method. Univariate associations between patient, disease, or treatment factors and OS and DFS were analyzed using Cox proportional hazards regression. Multivariate Cox regression models were built using factors with P<0.20 in univariate analyses. A two-sided P value <0.05 was considered to indicate statistical significance. Statistical analyses were performed using the "survival" and "survcomp" packages in R (version 2.11.1; R Development Core Team).

Results

General patient characteristics

In total, 428 patients fit the criteria for inclusion in this study: 31 treated with MIS approaches (17 robotic and 14 VATS) and 397 treated with thoracotomy (*Table 1*). Patients in the MIS group were older than those in the thoracotomy group (P=0.038). Adenocarcinoma was the predominant pathologic type in both groups but was observed more often in the MIS group (P=0.045). The distribution of sex, smoking status, pulmonary function, ASA (American Society of Anesthesiologists) score, clinical stage, and tumor cell differentiation were comparable between the two groups.

Operation-related and postoperative outcomes

Results of the surgical treatment in all patients are seen in *Table 2*. Operative complications, extent of resection, and final pathologic stage were comparable between the two groups. Perioperative mortality was comparable in both groups as well, although there were no deaths in the MIS group. Eight patients were converted to thoracotomy, for various reasons: five for extent of disease, two for severe adhesions, and one for bleeding. More stations of lymph nodes were sampled in the MIS group than in the thoracotomy group, but the difference was not statistically significant (P=0.081). Patients undergoing MIS had a shorter length of hospital stay (P<0.001). A higher proportion of patients in the MIS group underwent adjuvant therapy, primarily radiotherapy (61%) (P<0.001).

Survival comparison

The median follow-up was 40.7 months. Tumor recurrence or death occurred in 258 cases (222 deaths, 36 alive with disease) during follow-up. The median OS was 29.2 months for the MIS group and 45.4 months for the thoracotomy group; the corresponding 3-year OS were 48.3% and 56.6%. The difference between the groups was not statistically significant (P=0.84) (*Figure 1*). The only variable associated with OS on univariate analysis was age: older patients had a higher risk of death (P=0.027) (*Table 3*). In the multivariate analysis, only age was independently associated with OS (P=0.045) whereas clinical stage, forced expiratory volume in 1 second, and surgical approach (P=0.99) were not associated with OS.

The median DFS for the MIS and thoracotomy groups were 27.3 and 23.6 months, respectively; the corresponding 3-year DFS were 49.0% and 42.1%, respectively. The difference between the groups was not statistically significant (P=0.19) (*Figure 2*). No factors were associated with DFS in univariate or multivariate analysis (*Table 4*).

Discussion

Despite the increasing use of MIS in recent years, thoracotomy remains the most common approach for lobectomy in the United States (1-3), and the relative merits of MIS procedures for the treatment of locally advanced NSCLC in particular are unclear. For locally advanced NSCLC with established nodal metastases, multimodality therapy with induction chemotherapy is a feasible and preferred approach (22,23). However, utilization of MIS approaches is increasing, and it is therefore important to establish the role of VATS and robotics in the multimodality treatment of of patients with more advanced disease.

In this study, we compared survival and other outcomes in patients who underwent MIS compared with thoracotomy for lobectomy for NSCLC following induction chemotherapy. Our data showed that OS and DFS were comparable between the two groups, suggesting that in appropriately selected patients with locally advanced NSCLC, MIS approaches are feasible and can result in similar DFS and OS to those following thoracotomy.

Because of quicker in hospital recovery and reduced perioperative morbidity in certain patients compared with thoracotomy (1-6), MIS lobectomy has been used increasingly during the last decade, although no substantive prospective, randomized trials directly comparing the two have every been performed. It is interesting that we observed similar rate of surgical complications between approaches, perhaps due to the similar groups of patients all with locally advanced disease and good performance

Table 2 Operation-related and postoperative outcomes

Variables	MIS (n=31)	Open (n=397)	P
Deaths, n [%]	0	4 [1]	0.99
LOS, days, median (range)	4 [1–14]	5 [1–61]	<0.001
Conversion to open, n [%]	8 [26]	—	—
Sampled LN stations, median (range)	5 [3–7]	4 [1–9]	0.081
Complications, n [%]			
No	21 [68]	265 [67]	0.99
Yes	10 [32]	132 [33]	
Type of complications, n [%]			—
Cardiovascular	2 [6]	42 [11]	
Pulmonary	6 [19]	61 [15]	
Renal failure	0	3 [1]	
Chylothorax	1 [3]	2 [1]	
Hemorrhage	1 [3]	3 [1]	
Recurrent nerve palsy	0	4 [1]	
Wound infection	0	3 [1]	
Others	0	14 [4]	
Resection completeness, n [%]			0.71
R0	30 [97]	372 [94]	
R1/R2[a]	1 [3]	25 [6]	
Pathologic stage, n [%]			0.47[b]
0	2 [6]	29 [7]	
I	12 [39]	101 [25]	
II	5 [16]	90 [23]	
IIIa	11 [35]	170 [43]	
IIIb[c]	0	5 [1]	
IV[d]	1 [3]	2 [1]	
Type of adjuvant therapy, n [%]			<0.001[e]
Chemotherapy	4 [13]	43 [11]	
Chemoradiotherapy	1 [3]	24 [6]	
Radiotherapy	19 [61]	83 [21]	
None	7 [23]	243 [61]	
Unknown	0	4 [1]	

Data are no. [%] of patients, unless otherwise noted. ARDS, acute respiratory distress syndrome; LN, lymph node; LOS, length of hospital stay; MI, myocardial infarction; MIS, minimally invasive surgery. [a], including 6 cases with R2 resection, all in the thoracotomy group; [b], stage IIIa, IIIb, and IV combined; [c], four cases with metastatic lesions in different lobes on the same side of lung; 1 case with T4 invasion; [d], clinical stage IIIa cases at primary diagnosis; after induction therapy, solitary brain metastasis occurred; [e], cases with unknown adjuvant therapy have been excluded.

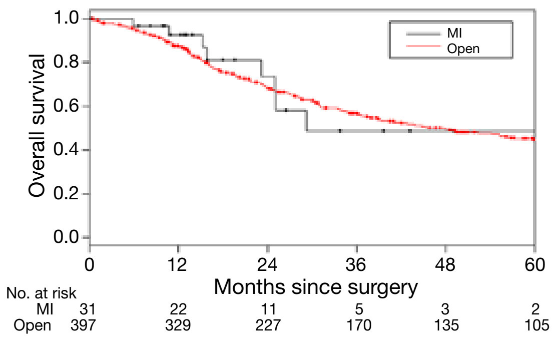

Figure 1 Kaplan-Meier curve for overall survival (P=0.84).

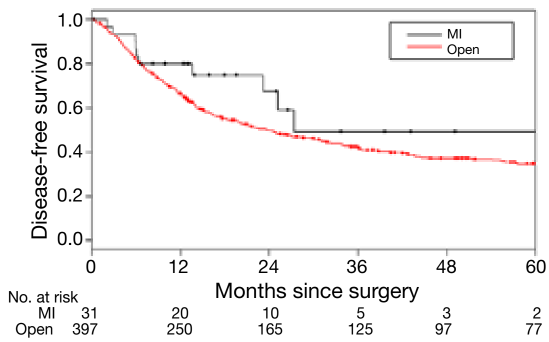

Figure 2 Kaplan-Meier curve for disease-free survival (P=0.19).

Table 3 Prognostic factors for overall survival (univariate analysis)

Variable	HR	95% CI	P
Age (continuous)	1.02	1.002–1.03	0.027
Sex (male *vs.* female)	1.18	0.90–1.53	0.23
Smoking			
Current *vs.* never	0.81	0.48–1.36	0.43
Former *vs.* never	0.79	0.52–1.20	0.27
Clinical stage			
IIB *vs.* IIA	1.49	0.87–2.57	0.15
IIIA *vs.* IIA	1.45	0.97–2.18	0.071
Pathologic type			
Squamous *vs.* adenocarcinoma	1.07	0.75–1.52	0.71
Other *vs.* adenocarcinoma	1.02	0.67–1.55	0.93
Cell differentiation			
Moderately *vs.* well	1.56	0.63–3.87	0.33
Poorly/undifferentiated *vs.* well	1.45	0.59–3.56	0.42
Unknown *vs.* well	0.97	0.38–2.47	0.95
FEV_1 (continuous)	0.99	0.98–1.00	0.17
DLCO (continuous)	1.00	0.99–1.01	0.50
Approach (open *vs.* MIS)	1.07	0.53–2.19	0.84

CI, confidence interval; DLCO, diffusing capacity of carbon monoxide; FEV_1, forced expiratory volume in 1 second; HR, hazard ratio; MIS, minimally invasive surgery.

Table 4 Prognostic factors for disease-free survival (univariate analysis)

Variables	HR	95% CI	P
Age (continuous)	1.01	1.00–1.02	0.15
Sex (male *vs.* female)	1.03	0.81–1.32	0.81
Smoking			
Current *vs.* never	0.75	0.46–1.21	0.24
Former *vs.* never	0.83	0.56–1.22	0.34
Clinical stage			
IIB *vs.* IIA	1.17	0.71–1.93	0.54
IIIA *vs.* IIA	1.29	0.90–1.84	0.17
Pathologic type			
Squamous *vs.* adenocarcinoma	0.92	0.66–1.29	0.30
Other *vs.* adenocarcinoma	1.22	0.84–0.64	0.64
Cell differentiation			
Moderately *vs.* well	1.99	0.81–4.90	0.14
Poorly/undifferentiated *vs.* well	1.59	0.65–3.89	0.31
Unknown *vs.* well	1.14	0.45–2.88	0.78
FEV_1 (continuous)	1.00	0.99–1.00	0.22
DLCO (continuous)	1.00	0.99–1.01	0.55
Approach (open *vs.* MIS)	1.53	0.81–2.88	0.19

CI, confidence interval; DLCO, diffusing capacity of carbon monoxide; FEV_1, forced expiratory volume in 1 second; HR, hazard ratio; MIS, minimally invasive surgery.

status. In addition, even though the only perioperative deaths were in the thoracotomy group (4/397) there was no difference in mortality. Length of hospital stay was shorter for the MIS group than for the thoracotomy group, likely due to shorter chest tube duration. However, due to the retrospective nature of the study we were lacking specific data in this regard, and this is one of the limitations of this study. These findings indicate that, with careful selection of patients, MIS approaches are safe and oncologically sound with potential benefits in hospital recovery.

In patients undergoing complete surgical resection adjuvant chemotherapy has been shown to benefit patients with pathological stage II-III disease (24,25). However, the ability for patients having a traditional thoracotomy to receive adjuvant chemotherapy has been limited. In the ANITA trial of adjuvant chemotherapy only approximately 60% of such patients were able to complete three cycles of treatment (26). Thus, at our institution even for clinical stage II disease we favor the use of induction therapy prior to surgical resection.

Long-term data on the use of MIS for locally advanced NSCLC are lacking. Hennon and coauthors from Roswell Park reported on 125 consecutive patients whom were evaluated for thoracoscopic lobectomy for advanced NSCLC (19). Eleven patients were excluded for chest wall involvement, and 19 patients had planned thoracotomy. Of the remaining 95 patients, 73 (77%) had successful MIS lobectomy. Only 19% of their patients underwent induction therapy. Like our findings, there were no differences in perioperative morbidity, mortality or survival. However, a higher proportion (37.2% *vs.* 5.2%) of the thoracoscopic group were able to undergo adjuvant therapy.

Huang *et al.* recently reported on 43 patients with NSCLC who were treated with VATS following induction therapy. They found good feasibility, good safety, and an acceptable 3-year OS (17). One patient underwent conversion, and seven patients were reported to have had a "hybrid" procedure for a total conversion rate of 19%. This is consistent with ours and other studies. Unfortunately, this study had only a single arm, and no comparison to standard thoracotomy was performed. Two other studies published recently also found good feasibility and safety for the VATS approach in patients with locally advanced NSCLC; however, most of the patients in these two studies did not receive induction therapy (18,20). Nakanishi and colleagues reported on 76 consecutive patients over a 9-year period, analyzing their results in three different time periods (18). Conversion rate was low (2.6%, 2/76), though the rate of bilobectomy (14.5%) and pneumonectomy (15.8%) were substantial. Gonzalez-Rivas and coauthors reported on 130 patients that had uniportal VATS for treatment of NSCLC (20). Forty-three patients were considered to have locally advanced disease without induction therapy. Complication rates were similar between early stage and advanced stage patients, suggesting VATS is feasible for more advanced disease. Once again pneumonectomy rate was 14%.

Our report has limitations. First, by nature of the disease and retrospective design of the study, there is considerable selection bias which may influence the comparison of outcomes between groups. Indeed, patients who underwent MIS approaches were older and tended to have lower stages of disease. The results should be interpreted as reflective of the current practice at our institution, in the context of careful selection of patients who are eligible for MIS. Definitive conclusions regarding comparisons between the two surgical approaches can be drawn only from randomized studies or larger matched case-control studies. Second, the sample size of the MIS group was small and reflects the experience of one tertiary care center. There were not enough individual VATS or robotic cases to conduct a relevant subgroup analysis to see if there are any advantages of robotics. Future multicenter studies are likely to provide more generalizable results.

In conclusion, our findings suggest that in appropriately selected patients with locally advanced NSCLC MIS approaches to lobectomy (VATS and robotic) following induction therapy are feasible and associated with comparable survival to that following thoracotomy. Additional multicenter studies are warranted to yield greater insight into the feasibility and validity of our findings.

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Footnote

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Robotic is better than VATS? Ten good reasons to prefer robotic versus manual VATS surgery in lung cancer patients

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Abstract: Different variants of minimally invasive lung resection have been described during the last decades including uniportal, non-intubated video-assisted thoracoscopic surgery (VATS), as well as, more recently, the subxiphoid VATS lobectomy. Robot-assisted thoracic surgery (RATS) is a relatively recent evolution of manual videoendoscopic surgery, born with the idea to make minimally invasive techniques an option even for complex procedures with the help of computer and micromechanics. Thus, after a period to gain confidence with the new system, robotic surgery found a great consensus among surgeons. With its development and diffusion in many surgical disciplines, including thoracic surgery, studies on its efficacy, safety and feasibility compared to conventional techniques have been performed. This has produced a healthy competition between VATS and RATS, even if these studies gave controversial results in terms of perioperative outcome and complications. A definitive conclusion is not available about a real benefit for the patients in the field of lung cancer treatment. Despite that, many aspects of robotic surgical platforms foreshadow that robotic systems will become an essential reality in the surgeon's armamentarium of the future. We expose the main features of robotic surgery to demonstrate that RATS is better than VATS to treat lung cancer patients.

Keywords: Robotic surgical procedures; robotics; minimally invasive surgical procedures; thoracoscopy

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The first video-assisted thoracoscopy is credited to a Swedish internist of the early twentieth century, Hans Christian Jacobaeus, who used a cystoscope to assist a closed intrathoracic pneumolysis, to treat tuberculosis, despite new findings suggest that video-assisted thoracoscopic surgery (VATS) was probably born half century earlier (1,2). Italy has a long history regarding the use of VATS and minimally invasive techniques in general (1). One example is the Forlanini's artificial pneumothorax in pre-antibiotics era, and the "Atlas thoracoscopicon" published by Felix Cova in 1928, that illustrates more pioneering findings during thoracoscopic procedures (3). At the beginning the VATS was reserved to simple diagnostic procedures, such as biopsies and only in the 80s we observed the evolution to VATS for major lung resection, thanks to the introduction of single lung ventilation and high-definition endoscope (4). In 1992 Roviaro and co-workers (5) proposed the first VATS lobectomy with anatomical hilar dissection, while Peracchia and colleagues (6) were the first to report its use to treat esophageal cancer. After that moment, a great number of authors from around the world described its safety and advantages when compared with thoracotomy, including a shorter hospitalisation, less postoperative complications and less postoperative pain, and most scientific societies established VATS as the standard procedure for early stage lung cancer (4).

Already since 1940, the concepts of "telemanipulation" and "telesurgery" were introduced (7). These words were created with the aim to perform complex tasks in dangerous and unhealthy places by machines, which were manipulated from the distant site. So that, engineers started to develop the first "performers", the ancestors of actual robots (7).

Many institutions recognize their potentials, so minimally invasive techniques were pooled with robotics to overcome the limitation of conventional procedures (7). The first robotic-assisted surgery was in 1983 during an orthopedic procedure. Later, robotics extended in neurosurgery, urology, gynaecology, cardiac surgery and so on, until 1993, when there was the first application of robotics in abdominal surgery with AESOP system (7). In 2001 ZEUS (Computer Motion Inc., Goleta, CA, USA) was introduced and it represented the real step towards a modern concept of general robotic surgery till the marketing of Da Vinci system, which remains the only available tool for the surgical applications till today (7).

Again, Italy had a role in the initial exploration of robotic applications with the publications of Giulianotti (8), who first used Da Vinci system for general and thoracic surgery, and Melfi (9), who described the first robotic lobectomy performed worldwide. Since that moment, the technological development contributed to spread the use of robotic surgery all over the world and the first comparative studies with traditional surgical techniques were published (10,11). Initially robot-assisted thoracic surgery (RATS) was considered a tool for privileged hospitals and criticized for the costs and for the complexity of the system (12); this is a common destiny of new technologies and revolutionary techniques. It is true that the studies, comparing RATS and VATS, did not demonstrate a definitive superiority of one technique over the other in terms of clear benefits for the patients, however these studies had some limitations, first of all VATS surgical teams had obviously a longer experience, than robotic ones, as the technique is older (12). Despite that, there are some indisputable peculiarities, which support the superiority of RATS over VATS, and convince us that robotics will be the minimally invasive technique of the future in particular for complex cases. More recent literature in addition demonstrated some clinical advantage of RATS compared to manual VATS. Here we present ten technical and general features to show why RATS is better than VATS.

(I) High-definition and three-dimensional vision: robotic system offers a stable camera platform, which facilitates a precise anatomical dissection while the distance between the screen and the table in VATS requires continuous adaptations of surgeons eyes to focalise the target and the field suffer of continuous movements due to human arms. There is no more necessity of a skilled camera operator like in conventional VATS procedure and, although the high definition is available also for VATS, RATS platform establish a stereoscopic vision with optimal depth perception (2). The console surgeons control the more suitable position of the camera and takes advantage of an eye-hand-target alignment (13). The magnification of the imaging permits to operate and to reach narrow spaces, like the mediastinum (2).

(II) Ergonomics: fatigue and musculoskeletal efforts related to prolonged standing are avoided, using the robot (2). The surgeon, sitting at the console in a relaxed position, can, especially during long and complex operations, concentrate himself in more accurate dissections and can spare energy, for unexpected difficulties. Furthermore, robotic is a women friendly tool, for the more comfortable position and tools, which do not require particular muscular strength.

(III) "EndoWrist" system: robotic instruments mimic the human wrist movements and empower human capability. They are characterised by 7-degree of angles with a 360-degree freedom rotation of movements (7). This allows reaching hidden spaces in the chest (2). Manoeuvrability allows more complex movements than VATS instruments, such as suturing parenchyma, or vessels, any type of precise and delicate dissection, saving anatomical delicate structures.

(IV) "Fulcrum-effect": robotic arms can rotate around a fulcrum point at the level of the trocar, avoiding the pressure on the ribs and the torque on the chest wall. It decreases damage to the intercostal nerves and surrounding tissues with less pain, and consequent reduction of analgesic use (14).

(V) Motion scaling and tremor filtering: the console translates the great movements of the surgeon in smaller and finest ones, in the meantime neutralizing the physiological human tremor (2). VATS instruments, on the contrary, being rigid and long, tend to amplify the small involuntary movements of the surgeons hands. The finer dissection, allowed by robotic tools, makes the field cleaner with reduced blood loss (13).

(VI) Ambidexterity, intuitive movement and surgeon independence: with the presence of the "master controllers", each hand can manoeuvre more than a robotic arm and control an instrument. Inside there are algorithms of human articulation of fingers, wrists and shoulders to mimic human arms (7). The possibility to use both hands for the dissection, with a forceps on the left side, and an instrument for dissection on the right side, increases precision in the procedure. The instruments should be a scissors, a bipolar dissector "Maryland bipolar", a monopolar hook or a spatula, according to surgeon's preferences; dissection is less offhanded and more anatomic, avoiding little spots of bleeding and ripping tissues, typical of conventional manual videothoracoscopy, that usually utilize just one hand. Finally, robot guarantees equivalence between hands, even in typical right handed surgeons and allows console-surgeon to control three robotic arms and camera; this permits greater autonomy in all passages of the operation, including positioning of the lung, thanks to the fourth arm, with exposition of small details of the surgical field and use of different dissecting tool thus avoiding the continuous need of the bedside assistant manoeuvre, thanks to the manual joysticks and pedals of the console.

(VII) Lymph-node dissection and upstaging: during VATS lobectomies, the most annoying phase is the mediastinal lymph node dissection due to narrow mediastinal space and uncomfortable and conflicting long rigid manual tools, while robotic hilar and mediastinal lymph nodes dissection is easier, more fluent and more agreeable than that performed on VATS or even open surgery. It is usually performed without any effort and rapidly, even in case of large lymph nodes and adhesions with delicate structures (7).

Despite no definitive conclusions can be made on data available in the literature as only few studies compared VATS and RATS in terms of lymph node dissection. According to Toker *et al.* (15) RATS resulted to be the procedure with higher number of dissected lymph nodes, compared to VATS or open surgery. In particular, there was a significantly higher in number of total N1 lymph nodes. One possible explanation of this result was related to the fact that surgeon has to remove the largest number of lymph nodes to favour the assistant surgeon in positioning vascular stapler (16). Conversely, in conventional VATS surgery the surgeon who makes the dissection is the same who usually cut the vessels, so manoeuvre depends on singular surgeon experience. Another relevant aspect to consider is that the robotic procedure is so precise that lymph node capsule does not break; therefore, a major number of nodes could be resected (15). Surely, number of lymph nodes dissected increases with experience, but robotic can have the same result of dissection of thoracotomy, even in early experienced surgeons (15). So that robotic surgery permits to discover a lot of occult nodes metastasis, allowing a more and more personalized oncologic adjuvant therapy to each patient.

In this sense, the upstaging is considered a consequence of the quality of the radical lymph node dissection, and determines the postoperative treatment of the patients. Park *et al.* (16) reported in their study a 21% rate of upstaging (16). A comparative review by Wilson and co-workers (17) showed that nodal upstaging in robotic-assisted resection was superior to VATS and similar to thoracotomy, if analysed by clinical T stage (17). The outstanding lymph node dissection can be attributed the large number of technical advantages of the robotic technique. However, we cannot exclude selection bias related to disease or preoperative staging reliability, such as patient with locally advanced lung cancer (stage III), tumors that require a very extensive resection (chest wall or vertebral resections), potentially more aggressive tumors (i.e., neuroendocrine carcinomas) and lack of the pre-operative staging (such as by mediastinoscopy or endobronchial ultrasound) for locally advanced disease (18). Velez-Cubian *et al.* (18) describe their experience with the demonstration that robotics facilitates dissection of occult nodal metastasis with results comparable, if not better, to VATS and thoracotomy (18).

(VIII) Learning curve: learning curve is the process of improving and increasing surgeons' capabilities in a specific technique (4). It seems that robotic surgery is easier to learn than conventional thoracoscopy, despite robotic technique requires a standardised and dedicated training too (19). Different investigators consider that approximately 20 robotic lobectomies are necessary to achieve competence (20-22); while 30–60 cases are considered an adequate number for VATS lobectomies (23).

(IX) Extended indications: many studies demonstrate that surgeons do not require necessarily a particular

VATS experience to use robotic surgery (13). The dedicated training, the standardization availability of have a standardised procedure and the precise and intuitive technology (i.e., master controllers used as joysticks or the pedals at the console) seem to make surgeons more confident in robotics. RATS can be used to afford more complex operations than VATS and thus expand indications of minimally invasive surgery. This is related to the easier capability of suturing in case of sleeve resection, the delicate isolation of thin and fragile structure in anatomical segmentectomies and the guarantee of radical lymph node dissection in case of locally advanced disease resection, that in VATS are avoided by most surgeons.

(X) Data integration and connectivity: with new digital platform, integrated in the robotic system, the surgeon has the possibility to switch from full-wide screen to a multiple-image mode, through auxiliary accesses (electrocardiography, echocardiography, CT, etc.) (7). He can be always updated on the patient parameters and status, and review images, exams of the patient. These aspects contribute to determine surgeons' independence and decision making.

These are the main aspects in support of robotic technique.

The quality of surgery has an impact on the post-operative patient outcome, despite controversial data have been observed in retrospective comparative studies on complications, and length of stay, some benefits seems to be related to RATS in the study of Farivar *et al.* (24). Data from two institutions were collected and matched with those of the Society of Thoracic Surgery (STS) National Database. A significantly decrease in 30-day mortality and postoperative blood transfusion was observed after robotic lung resection compared to VATS and thoracotomy. Furthermore, the patients were discharged two days earlier than VATS and 4 days earlier than open surgery (24). Similarly, Louie *et al.* (25) found the same results. They thought that robotic technique favoured in patient comfort and mobility, which translated in an earlier discharge (25). About bleeding Louie and colleagues' experience showed that there was no difference in the overall rate of reoperation between the two groups, but proportionally more patients in the VATS group returned to operating room for bleeding (25).

The main argument against RATS over VATS is the increased cost. The high costs of purchase, maintenance and consumables are a concern and continue to limit uptake of robotic system in thoracic surgery, despite few comparative data are available from prospective studies. In particular, such analysis are lacking in the European contest. On this point, we have preliminary data indicating slightly increased costs for RATS versus VATS, but all falling into the profit area in a private Hospital of Northern Italy. Other data also indicate that hospital can make profit from robotic thoracic surgery, as costs seem to be lower than reimbursement from paying bodies. Most studies, however indicate that robotic surgery for lung cancer is more expensive than VATS and open surgery. Today only one producer has marked an effective robotic surgical system, but new robots are being developed by Medtronic and by Verb Surgical. Entry of new surgical robot manufacturers onto the market will bring much-needed competition that may also lead to cost reduction.

From technical point of view some limitations were emphasized at the beginning, such as the spatial footprint of the apparatus, the complexity in installing the robot's arms into the patient's chest and operating at a distance from patient was also considered source of anxiety by many surgeons. As a result, time was needed to gain confidence with the new apparatus. In the mean while advantages related to improved vision over the operative field, increased comfort for the surgeon and the precision of the manipulation became progressively more appreciated.

Robot technology has made enormous strides to date, but in the near future we expect improvements beyond the actual use of robot-assisted surgery. The future developments of this technology will involve simulation, 3D modelling and augmented reality with the possibility to plan preoperatively the surgical intervention and intraoperatively superimposing preoperative data onto a real-world view of the patient. In a far future robotisation of the procedure, replacing the human gesture with robotically automated one will be a possible evolution with new digital surgical platforms combining advanced visualization, with innovative instrumentation, connectivity and robotics.

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Footnote

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Pulmonary Surgery

Robotic lobectomy: an essential addition to the minimally invasive armory

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As the only robotic system approved by the United States Food and Drug Administration for lung surgery, the Da Vinci System (Intuitive Surgical, Sunnyvale, CA, USA) is gaining popularity worldwide as an important alternative to the conventional minimally invasive surgical approach of video-assisted thoracic surgery (VATS). The robotic system is considered a significant evolution in the development of surgical tools, allowing the surgeon to view the surgical site in three dimensions and perform the operation via a console located near the operating table. The endo-wrist instruments attached to the robotic arms provide a wide range of precision movements with greater dexterity. Moreover, the hand tremor of the surgeon can be filtered out by using a 6-Hz motion filter, which guarantees precise micro-movement around vital structures.

Many researchers believe that the robotic system will reduce the number of procedures needed to master a skill compared with traditional thoracoscopic surgery, especially for experienced VATS surgeons (1). By creating a regression trend-line and defining the learning curve as the change in slope corresponding to the beginning of the plateau, Meyer *et al.* (2) found that the learning curves for robotic assisted lobectomy were 15, 20, and 19 cases for operating time, mortality, and surgeon comfort, respectively. Subsequently, Veronesi *et al.* (3) reported the first study comparing muscle-sparing thoracotomy and robotic assisted lobectomy using propensity score matching. The conversion rate to thoracotomy was 13% with the robotic arm. The two groups had similar postoperative complications and numbers of lymph nodes resected (robotic, 17.5 *vs.* open, 17). The hospital stay was longer with the thoracotomy arm (6 *vs.* 4.5 days) after excluding the initial 18 cases that underwent robotic lobectomy, whereas the robotic (n=36) operating time was approximately 60 minutes longer. The authors also note that the operation duration decreased by 43 minutes after the initial stage, indicating that the surgeons' proficiency led to better performance with the robotic surgery.

Nevertheless, clinicians may be more interested in the technical aspects of the two minimally invasive approaches. The recent *Annals of Thoracic Surgery* article by Louie *et al.* (4) compares VATS and robotic lobectomy for stage I and II lung cancer using the Society of Thoracic Surgeons General Thoracic Surgery Database. The study included 1,220 robotic lobectomies performed from 2009 to 2013 and these patients had more comorbidities (e.g., coronary heart disease, hypertension) compared with the VATS group (n=12,378). Operative measurements were similar, except for the significantly longer operating times needed for robotic lobectomy (186 *vs.* 173 minutes). The postoperative complications and 30-day mortality were equivalent in the two modalities, and concurred with the rate of nodal upstaging defined as clinical N0 to pathological N1. Interestingly, the median postoperative length of hospital stay was 4 days for each group, although a lower proportion of the cases undergoing VATS lobectomy had hospital stays of less than 4 days (39% *vs.* 48%). One possible explanation, as stated by the authors, is that centers with high volumes of robotic surgery would have mature protocols regarding early discharge.

Despite the growing number of studies showing perioperative measurements similar to those of VATS, one of the major concerns preventing widespread adoption of robotic-assisted lobectomy is the lack of adequate long-term survival data. The first large cohort study was that of

Park *et al.* (5), in which 325 robotic lobectomies achieved a 5-year overall survival (OS) up to 91% for stage IA, and 88% for stage IB, with a median follow-up of 27 months. In a recent study, the same group found that the results of robotic, VATS, and open lobectomy were equivalent from an oncologic perspective (6). The median follow-up time was 52.7 months for all participants and 39.8 months for the robotic approach. The 5-year OS was 77.6%, 73.5%, and 77.9% (P>0.05) for the robotic (n=172), VATS (n=141), and thoracotomy (n=157) patients, respectively. Interestingly, slightly longer disease-free survival (DFS) was observed with the robotic arm (72.7%), as compared with 65.5% and 69.0% in the VATS and open groups, respectively (P=0.047). However, the surgical approach failed to demonstrate a significant association with a better OS and DFS; therefore, the minimally invasive approaches achieved similar survival to thoracotomy in stage I lung cancer following lobectomy. In another study (7), it was also concluded that robotic and VATS approaches had similar R0 resection rates and postoperative survival in comparison with thoracotomy for treating locally advanced lung tumors, although the strength of this result was limited as only 17 robotic procedures were enrolled.

Robotic lung surgery has the advantage of visualizing and dissecting lymph nodes around delicate vessels, resulting in the removal of more lymph nodes stations (6). However, for those who play "devil's advocate" regarding robotic lobectomy, the absence of haptic/tactile feedback raises concerns regarding hemorrhage control, especially when the assistant rather than the surgeon passes the stapler across the pulmonary vessels. The latter for example has been addressed by the industry by providing their robot's own surgeon operated staplers. Nevertheless, clear communication between the surgeon and assistant is vital to avoid iatrogenic accidents, and it has been suggested that a rolled-up sponge be kept ready while working around vascular structures for better control of bleeding (8). Another potential drawback of robotic lobectomy lies in the inability to reduce the working ports needed for the procedure. Although Cerfolio *et al.* (9) has proved the feasibility of positioning four robotic arms along a single rib space, the recent prevalence of single-port VATS (10) has the theoretical merits of minimizing the damage to the intercostal nerves and further reducing the surgical access trauma. Moreover, recent advances in the scope system (11), wrist-like rotational device (e.g., FlexDex; FlexDex, Brighton, MI, USA) (12), and integrated flexible uniportal surgical system (e.g., SPIDER surgical system; TransEnterix, Durham, NC, USA) (13) have contributed to closing the ergonomic gap between VATS and robotic lobectomy. Furthermore, the rapid development of single port robotic surgery may finally provide the answer to single port VATS in terms of single incision access trauma (14).

Cost-efficiency remains another concern that hinders the widespread use of robotic lobectomy. The first findings came from a study conducted in 2008, in which Park and Flores (15) demonstrated that the average cost of a robotic lobectomy was less than that of a thoracotomy due to the shortened hospital stay, but it was still greater than that of VATS. Considering the high purchase and maintenance costs for the robot, and the slightly longer operating time, a robotic lobectomy costs an additional $3,000 to $5,000 per case when compared with VATS alone (16). However, many researchers agree that with the increased experience of the surgical team and modifications of the techniques, the cost of robotic surgery will be decrease gradually.

Despite efforts to promote minimally invasive surgery in recent decades, a thoracotomy was still used in 56.5% of the lung resections performed in the United States in 2010 (17). The camera tremor and reduced dexterity of instrumentation may lower the surgeon's willingness to use the VATS approach. In terms of robotics, Louie *et al.* (4) found that the majority of robotic cases were performed by only 22 groups, and one third of them were done at four centers. Since the current evidence indicates that the robotic approach is equivalent, or at least not inferior, to VATS lobectomy, one may foresee that the true value of robotic surgery is in increasing the proportion of surgeons that use a minimally invasive approach.

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Robotic assisted VATS lobectomy for loco-regionally advanced non-small cell lung cancer

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Abstract: Despite lung cancer screening programs and efforts at early detection, patients with non-small cell lung cancer continue to present with loco-regionally advanced disease. In particular, patients with positive mediastinal lymph nodes (N1/2, stage II/IIIA) present a challenge to the thoracic surgeon. The thorough lymphadenectomy required by these patients can be difficult to perform with standard VATS approaches. In addition, hilar fibrosis may result from the neoadjuvant therapy these patients generally receive, which complicates dissection of the vascular and bronchial structures. The robotic approach offers benefits that can help to address these challenges. While not ideal for the surgeon just learning robotic surgery, in experienced hands this is an effective tool to deal with loco-regionally advanced lung cancer safely and with optimal oncologic efficacy.

Keywords: Carcinoma; non-small-cell lung; surgical procedures; robotic; telerobotics

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Introduction

Despite advances in lung cancer screening and early detection, a significant proportion of non-small cell lung cancer (NSCLC) patients present with advanced disease (1). Thankfully, even with loco-regionally advanced NSCLC, surgery can offer an increased chance of cure when employed as part of a multi-modality treatment plan (2). The definition of loco-regionally advanced NSCLC includes diverse presentations, including chest wall invasion, major vessel invasion, central tumor location and extensive nodal disease. This paper focuses on the surgical management of clinically apparent hilar and mediastinal nodal involvement, especially in the post-neoadjuvant therapy setting. These operations can be technically more challenging than early stage disease, with respect to dissection of the bronchovascular structures and ability to resect disease.

In the early experience with video assisted thoracic surgery (VATS) lobectomy for NSCLC, locally advanced disease was considered a contraindication (3). However, there have been increasing reports of the use of the VATS approach for many types of loco-regionally advanced NSCLC, including pneumonectomy (4), chest wall resection (5), superior vena cava resection (6), carinal and sleeve resections (6,7) and superior sulcus tumor resections (8). However, a more common use of minimally invasive surgery for loco-regional disease is in dealing with clinically apparent hilar or mediastinal adenopathy (N1/2, stage II/IIIA). VATS lobectomy has been compared against thoracotomy for stage IIIA patients following neoadjuvant chemotherapy with equivalent perioperative outcomes and a trend towards improved survival with VATS (9). Possible oncologic benefits of minimally invasive approaches include less immune derangement due to decreased inflammatory response (10) and increased delivery of adjuvant chemotherapy (11).

At Memorial Sloan Kettering Cancer Center (MSKCC), open, traditional VATS and robotic-assisted VATS approaches are all used in patients with stage II/IIIA disease following neoadjuvant therapy. Recently, the results of the robotic-assisted and traditional VATS resections were compared with the open approach over 10 years at MSKCC (12). Compared to thoracotomy, the minimally invasive group had a similar R0 resection rate, postoperative morbidity and 3-year overall and disease free survivals, with a shorter length of stay. With increasing experience with the robotic-assisted approach it has become the senior author's preferred approach to these patients because of the benefits of improved visualization, dexterity and accuracy. A recent retrospective review of the oncologic results of robotic lobectomy for NSCLC demonstrated low operative morbidity and mortality with long term survival consistent with published results for VATS and thoracotomy (13).

Patient selection and work-up

Selection of patients with cII/IIIA disease for surgical resection is a complex and controversial issue, involving assessment of the extent of local and mediastinal nodal disease, underlying cardiopulmonary function and comorbidities as well as response to induction therapy. The optimal neoadjuvant therapy for IIIA NSCLC has not been defined and options include both chemotherapy and chemoradiation. At MSKCC patients are reviewed by a multidisciplinary tumor board involving thoracic surgeons, medical and radiation oncologists, pathologists and radiologists. Appropriate patients are selected for multi-modality therapy. Our most common practice is to use neoadjuvant chemotherapy prior to surgery except for certain clinical scenarios such as superior sulcus tumors where induction chemoradiotherapy has been shown to be associated with improved outcomes (14).

With regard to selecting patients with loco-regionally advanced NSCLC for robotic-assisted resection, the most important factors are the anatomy of the patient and disease. Careful review of both pre- and post-neoadjuvant imaging studies is critical to identify potential problem areas. Local hilar invasion by the primary tumor, bulky hilar or mediastinal lymphadenopathy or the presence of calcified lymph nodes should prompt serious consideration of an open approach.

Preoperative preparation

Preparation of the entire surgical team is critical to success in any operation, in particular when advanced technology is involved as in robotic-assisted VATS. Our approach to training our team to perform robotic lobectomy has been previously described (15). All of the members of the multidisciplinary team in these cases should be thoracic surgery trained and familiar with both the technique of VATS lobectomy and the robotic platform being employed. As with any new technique, a learning curve for robotic lobectomy has been described (16). Surgeons must be aware of their own limitations and not to undertake these more challenging loco-regionally advanced resections until they have acquired an adequate level of robotic skill.

Figure 1 Room set-up for robotic lobectomy.

We preferentially employ the da Vinci Surgical System Xi robot for pulmonary resection. This system provides robotic control of three working arms and a 30 degree telescope. In general, the robot cart is brought in from posterior to the patient at approximately 90 degrees from the spine. The room set-up is depicted in *Figure 1*. The Si system may also be used effectively for lung resection but lacks advantages such as more flexible cart positioning, automated targeting, less need for wide spacing of robotic arms and the ability to use robotic staplers.

Pre-operative DVT and antibiotic prophylaxis is used as for any anatomic lung resection for cancer. We do not routinely use epidural catheters for analgesia.

Equipment preference card

The main instruments used are:

I. Bipolar fenestrated robotic forceps for dissection and cauterization;
II. Tip-up fenestrated grasper for lung retraction;
III. Cautery spatula for cauterization and dissection;
IV. Hand-held powered stapler;
V. VATS suction and grasping forceps, used by the bedside assistant.

Procedure

General anesthesia with single lung ventilation is employed, generally via a double-lumen endotracheal tube. The patient is positioned in the lateral decubitus position with all pressure points padded and the table flexed.

Figure 2 Incision placement for robotic lobectomy.

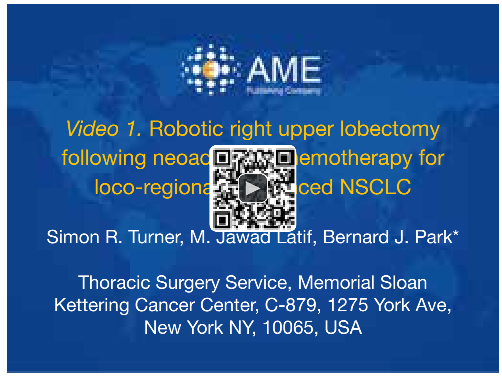

Figure 3 Robotic right upper lobectomy following neoadjuvant chemotherapy for loco-regionally advanced NSCLC (18). Available online: http://www.asvide.com/articles/1375

Figure 4 Robotic right lower lobectomy following neoadjuvant chemotherapy for loco-regionally advanced NSCLC (19). Available online: http://www.asvide.com/articles/1376

Three ports are used for robotic access, as well as a non-rib spreading utility incision (*Figure 2*). The camera port is placed first in the 7th or 8th intercostal space in the posterior axillary line. A 12-mm port is placed in the 9th intercostal space posteriorly for one robotic working arm and the hand-held powered or robotic stapler. An 8-mm port is placed in the 5th or 6th intercostal space posterior to the scapula for the tip-up fenestrated grasper used primarily for lung retraction. A 2.5–3 cm utility incision is placed in the 5th intercostal space at the posterior axillary line to lie over the hilum, through which the final robotic working arm is introduced. The bedside assistant can work around the port in this incision for additional retraction and suction as well as specimen retrieval; however, an additional 5-mm port placed between the camera and the access incision often allows better angles for the suction. A total portal approach has been described (17); however, we prefer this approach as it allows easy access for hemostatic control if needed and more closely approximates the traditional VATS setup allowing for easier transition by trainees and new surgeons. Furthermore, some form of access incision is required for specimen removal regardless of approach. As a general rule, the cautery spatula is controlled by the surgeon's dominant hand and the bipolar fenestrated forceps are controlled by the non-dominant hand. We do not typically employ insufflation of the chest cavity, but it may be done with a total portal approach when increased exposure is desired. Short videos of right upper (*Figure 3*) and right lower (*Figure 4*) lobectomy after neoadjuvant therapy for nodal disease are included for reference.

Our approach to pulmonary resection begins with a complete mediastinal lymph node dissection, and this is especially important in loco-regionally advanced disease. Thorough nodal dissection is the only way to ensure an R0 resection in this setting and also facilitates safe isolation and division of the hilar vascular and bronchial structures. Node dissection begins with division of the inferior pulmonary ligament allowing dissection of stations 8 and 9. Proceeding superiorly along the posterior hilum, stations 7 and 10 are dissected next. The lung is then retracted posteriorly and the anterior mediastinal and hilar nodes are also dissected. In loco-regionally advanced disease following induction therapy some degree of hilar and mediastinal fibrosis should be anticipated. The enhanced visualization and dexterity of the robotic approach makes the nodal dissection easier and a more complete lymph node removal may be the result, with potential oncologic benefits (20). Attention should also be paid in these patients to areas of visible lymphatic leak which may be clipped, preventing high chest tube losses in the postoperative period in these patients.

Next the hilar structures are isolated and divided. Again, the possibility of hilar fibrosis must be kept in mind, especially when dissecting the pulmonary artery. Key to safe robotic surgery is learning to rely on visual cues to judge the tension being placed on fragile tissues, as haptic feedback is lost. With experience, the improved, three-dimensional vision afforded by the robot can make up for this deficit. Flexibility with regards to the order in which hilar structures are divided is important in any lung resection, and in particular after neoadjuvant therapy where fibrosis may make approach from one angle more difficult than another. Generally, the vein is divided first, followed by the arterial branches and finally the bronchus but this order is altered as needed based on intraoperative findings. The hand-held powered stapler is used to divide most of these structures, as it provides a steadier firing platform than traditional staplers, especially when used by trainees or physician assistants at the bedside who may have less experience. It is also more cost-effective compared to the Xi robotic stapler. However, for critical structures such as the most proximal arterial branches to the upper lobes, the robotic stapler offers several advantages, such as the dexterity and degrees of freedom afforded by robotic instrumentation, as well as direct control by the operating surgeon over the passage of the stapler. We do not routinely use tissue flaps to buttress the bronchus staple line even after neoadjuvant therapy, though this can be considered on a case by case basis.

Role of team members

One advantage of the robotic approach to lobectomy is the ability to decrease the number of assistants needed to perform the case. Unlike in traditional VATS lobectomy where often a skilled first assistant as well as an additional camera operator are employed, in robotic lobectomy only one skilled bedside assistant is required. The role of this assistant is in exchanging robotic instruments as necessary as well as providing additional retraction, suction and removing specimens such as lymph nodes via the assistant port. This has the side-benefit of freeing up surgical trainees for educational opportunities to perform parts of the operation on a second operator console. Skilled scrub and circulating nurses or surgical technicians complete the team.

Post-operative management

The post-operative management of patients following robotic assisted VATS lobectomy should be no different than any VATS lobectomy patient. Chest tubes are set to water seal and removed once the daily output is less than 400 cc/day, assuming it is not chylous or excessively bloody. Early ambulation, deep breathing and coughing with good pain control are essential, and are facilitated by the minimally invasive approach. Patients are often ready for discharge by the second or third postoperative day.

Tips, tricks and pitfalls

Patient Selection: Careful patient selection is key to success in any surgical procedure, especially in the setting of advanced disease. Patients must be appropriately screened from an oncologic point of view to ensure they are good candidates for multi-modality treatment.

Thorough lymphadenectomy facilitates hilar dissection

In the setting of loco-regionally advanced NSCLC after neoadjuvant therapy, careful dissection of hilar structures is critical to avoid injury. Thorough mediastinal and hilar lymphadenectomy exposes vascular and bronchial structures at their branch points. Lymphadenectomy is also critical in loco-regionally advanced disease to eradicate any viable tumor and provide the best chance of cure.

Empowerment of qualified assistants

Early in our experience with robotic lung resection we performed each case with two attending surgeons. However, we are fortunate to have a talented group of thoracic surgical physician assistants who have taken an interest in VATS and robotics. By providing graduated responsibility to these PAs, they have gained considerable skill in providing bedside assistance. This allows us to perform these cases with only the PA at the bedside performing tasks such as stapling the pulmonary artery branches. This means only one surgeon is needed for each case, and thoracic fellows can work at the teaching console to gain robotic skills.

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Footnote

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VATS, robotic lobectomy and microlobectomy—the future is just ahead?

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Abstract: Video assisted thoracoscopic surgery (VATS) lobectomies have been instrumental in the evolution of thoracic surgical oncology since its introduction in the early 90s. Although there is no robust data to confirm or refute its superiority over open conventional lobectomy, there have been a number of meta-analyses which have shown that VATS is safe and feasible for those undergoing radical resection for cancer. Over the years, VATS lobectomy has continued to evolve with newer techniques, less ports and better instruments. There is now an interest in performing uniportal VATS lobectomy and this is now moving to one without a need for incision in the intercostal space. Microlobectomy, originally envisaged by a group of surgeons from 6 different centres and involves using subcentimeter incisions alongside a subxiphoid utility port. Some of the technical disadvantages of VATS are that the images are 2-dimensional (2D), there is limited depth perception; and manoeuvring rigid instruments within the limited confines of the chest can make dissection difficult. The advent of robotic lobectomy has addressed some of these problems. The 3D vision is unparalleled, the endowrist seamLessly mimic human hand movements and the instrument movement within the chest is fluid. However, the high capital costs may deter smaller centres from introducing this service, especially when working within a limited budget in the public hospital. This can be circumvented by ensuring that the robot is used in a multi-specialty setting and concentrated in a few high volume tertiary centres.

Keywords: Lobectomy; video assisted thoracoscopic surgery (VATS); robotic; microlobectomy; lung cancer; resection

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Introduction

Jacobeus first pioneered the use of a thoracoscopy in 1910 for lysis of adhesions and drainage. Following that, in 1921, he published his extensive experience in pleuroscopy for diagnostic purposes (1). Over the next 60 years, minimally invasive procedures gained a foothold and the phenomenal success of laparoscopic surgery fuelled the interest in other specialties.

Video assisted thoracoscopic surgery (VATS) lobectomies have been instrumental in the evolution of thoracic surgical oncology since its introduction in the early 90s. Although there is no robust data to confirm or refute its superiority over open conventional lobectomy, there have been a number of meta-analyses which have shown that VATS is safe and feasible for those undergoing radical resection for cancer. Multiple observational studies have shown that the rates of post-operative morbidity are lower than for conventional surgery, in particular complications such as pain, incidence of pneumonia and cardiac arrhythmias; VATS patients also have reduced length of stay compared to open procedures. Furthermore,

more patients undergoing VATS receive adjuvant treatment and at higher doses (2). The SCTS Thoracic surgery database for the UK and Eire have shown mortality rates of 1% for VATS compared to 2% for conventional open procedures (3).

VATS lobectomy

The definition of VATS in the early studies varied according to the surgeon or centre performing them. The consensus definition, first described in the CALGB 39802 trial (3), of a VATS lobectomy is as follows (4):

(I) One 4- to 8-cm utility access port;
(II) Between one to three 0.5-cm port incisions;
(III) Used videoscopic guidance;
(IV) Traditional hilar dissection;
(V) No rib-spreading.

Concerns were raised about the oncological adequacy of VATS. This is because of the perceived idea that lymphadenectomy in VATS would be more difficult. Cao *et al*. (5) and Yan *et al*. (6) have shown that VATS is safe and the oncological outcomes are similar to conventional open lobectomy. Mediastinal lymph node dissection (MLND) during VATS lobectomy has shown to be equally efficacious to open lobectomy (7).

However, the demand for VATS procedures is patient-driven. The arguments in favor of VATS lobectomy include cosmesis, less postoperative pain, shorter length of stay, and relative lower overall cost (8). Despite the apparent benefits of the minimally invasive approach, the uptake for VATS amongst surgeons is still low. Data published by the SCTS in the UK show that only 30% of lung resections are performed via VATS, although that varied from unit to unit. In the US, the figure is closer to 50%, while in Japan, >50% of cases are performed with VATS (9). This is multifactorial but can be broadly put down to the following reasons (10):

(I) Technical issues, 2D vision and limited maneuverability;
(II) Lack of adequate training;
(III) Concerns about major vascular injury and control of bleeding.

There is no doubt that the learning curve is initially steep but once surgeons were comfortable performing minimally invasive radical resection for lung cancer, the envelope was pushed further out. Smaller and smaller incisions were made and the number of ports decreased from the initial 3-4 port to 1-2 port techniques. The utility incisions were usually made in the intercostal spaces to allow multiple instruments to be used for dissection and retraction. However, movement of instruments in and out of the port sites may cause neuropraxia, which may give rise to long-term neuropathic pain that can be disabling. Additionally, removing a large, air-trapped lobe or a lobe containing a large tumour from the same intercostal space can compound the problem further.

Uniportal VATS lobectomy

Single-port pulmonary resections were initially described by Rocco and colleagues in 2004 and they have published their 10-years experience in uniportal VATS surgery for diagnostic and therapeutic procedures (11).

Uniportal VATS lobectomy has been pioneered by Gonzales-Rivas in Coruna and is now being used for complex resections including pneumonectomies, sleeve resections, redo surgery and tumours with chest wall involvement. The operative time was higher in patients with advanced tumours but duration of chest tube drainage, length of stay and complications were similar (12).

Subxiphoid utility incision—a step away from the intercostal spaces

In parallel there has been a renewed interest in subxiphoid surgery which is not a new concept in thoracic surgery. In 1999 a technique was described for metastasectomy by VATS which included a subxiphoid port to allow manual palpation of all lobes in both hemithorax without the need for a mini-thoracotomy (13,14). This subxiphoid approach also enabled mediastinal masses to be removed with a single incision (15).

The subxiphoid approach has more recently been expanded with novel subxiphoid uniportal approaches for thymectomies and lobectomies from innovators in the Far East (16-20). Most recently Jiang and colleagues from the Shanghai Pulmonary hospital published a series of 153 cases of lobectomies of every lobe and 48 segmentectomy using this approach (21).

This technique essentially obviates the need for making a large incision in the intercostal space and thus, reduces damage to the intercostal muscles and neurovascular bundle. For example, in order to remove tumours of 2–5 cm, it is often necessary to incise the intercostal muscles by 8–10 cm to allow the ribs to separate without causing fractures. This is more so in larger tumours and patients with air trapped lungs.

Additionally, patients tolerate incisions in the upper abdomen much more than in the intercostal space—this will allow them to perform their deep breathing exercises and cough and clear their secretions. Another way of minimising post-operative pain is to place the intercostal chest tube to be placed via the subxiphoid port. Thus, the incidence of long-term neuropathic pain should be much less.

Another benefit of the subxiphoid port is that either pleura can be entered easily under direct visualisation. This incision allows a 12 mm CO_2 port to be placed and thus, can be useful for CO_2 insufflation, retraction and stapling using the conventional endo staplers. Alternatively, A wound protector system can be used (Alexis Wound Retractor; Applied Medical, Rancho Santa Margarita, CA, USA). The port enables access to all the hilar structures with minimum articulation of the endo staplers and also allows the fissure to be developed when using staplers. Naturally, VATS using the subxiphoid port has evolved into a totally uniportal VATS without any intercostal incisions.

Robotic lobectomy

VATS techniques using conventional endoscopic instruments only allows two-dimensional (2-D) visualization although more recently, 3-D cameras and monitors along with 3-D glasses have been used. There may be a variety of reasons why surgeons are not keen to take up VATS lobectomy and they are mostly technical. The main drawback of VATS has been the 2-D vision with minimal range of amplification, which can make hilar and fissural dissection more difficult especially since depth perception is also limited. Hand-eye coordination can be difficult as the monitor is usually further away from where the surgeon is working.

Newer articulating instruments including endo staplers and cameras have helped to overcome some of the difficulties of having 2-D vision; and this allows dissection around the vessels and lymphadenectomy to be performed safely. These instruments however, have not really been able to completely replicate the 360-degree movement in the operators' wrists, and the ergonomics still have a long way to go, especially within the limited confines of the thoracic cavity. Furthermore, pivoting the instrument in the intercostal spaces can cause significant neuropraxia, which hinders the patients' recovery. Fine dissection in the mediastinum can be more difficult because tremor amplification. Another consideration is the larger radius of the movement curvature inside the chest when pivoting an instrument (22,23).

Advocates of robotic lobectomy state that this procedure addresses some of the concerns mentioned above. The superior imaging and 3-D camera offers unparalleled vision and magnification. The robotic endo-wrists allow precise movements of the instruments inside the patient, following the natural movements of the surgeon's wrist. Advantages of robotic compared to conventional VATS include the additional four degrees of freedom (internal pitch, internal yaw, rotation and grip), the elimination of the fulcrum effect, reduced human tremor and improved ergonomic position for the surgeon (24).

Hand-eye coordination is maintained as the monitor and endo-wrists are located on the same console. The camera is manipulated at the console using the endo-wrists and a dedicated foot pedal. It allows variable magnification, high-definition stereoscopic images to the monitor, which may compensate for the absence of haptic feedback (25).

Although there is a paucity of robust randomized controlled trial data comparing robotic lobectomy to VATS or even thoracotomy—a few studies from the US and Europe report comparable perioperative outcomes to the results of a recent systematic review on conventional VATS (6).

Complications types and the rates are comparable to VATS lobectomies and perhaps lower than open procedures. There is no randomized controlled trial to assess the oncological outcomes following robotic lobectomy but Park *et al*. published a retrospective multi-institutional review on 325 patients undergoing robotic lobectomy for early-stage NSCLC. The conversion rate to thoracotomy was 8%, with an overall morbidity rate of 25.2%. In hospital death was only 0.3% and the median length of stay was 5 days. The overall 5-year survival was 80% after a mean follow up period of 27 months. The oncological effectiveness can only be ascertained when longer term data is available. However, the rate of upstaging stage I NSCLC is 21% (26), which is much higher than the 11.6% reported for VATS and 14.3% for open procedures (27).

The limitations of robotic lobectomy include the initial period where the learning curve is steep. However, a figure of 20 cases is quoted by three studies as the volume required to attain necessary skills in robotic surgery (5). Results from Cao's systematic review identified that highest conversion rates and operating times were from institutions that performed <30 cases. Therefore, adequately trained specialised anaesthetists, scrub staff, and assistants are mandatory to enable a robotic lobectomy program to achieve a satisfactory outcome. Furthermore, these cases should be performed in high-volume tertiary care centres to allow effective multi-specialty usage of the robot. This subsequently increases efficiency and savings especially in terms of cost for initial capital, consumables and training. If two consoles are available—training, teaching and proctoring in robotic lobectomy is possible. In the UK, the first two centres to start a robotic lobectomy program are in the North East of England (Freeman and James Cook University Hospitals) and the regular teaching/training of registrars/residents will now be the next phase. We should look to our urology colleagues in the UK where robotic surgery has been incorporated into the curriculum for its residents and trainees.

In a nationalized public healthcare system such as the National Health Service, one of the primary considerations of a clinical commissioning group which funds hospital trusts would be the cost effectiveness of a procedure. The initial outlay or capital cost would be the biggest—Park *et al.* reported that the initial capital cost of the da Vinci robot system was about a million USD in 2008. The costs for each operation are USD 3—4,500 more when compared to VATS (28). However, thoracotomy costs are higher as the patients have longer intensive care and in-hospital total length of stay (29). Indeed, NHS England are currently reviewing the cost-effectiveness of robotic lobectomy and this potentially may have an adverse impact into the future provision of services in the UK.

In summary, robotic lobectomy is feasible and can be performed safely for selected patients in selected high volume tertiary care centres. However, high costs and the paucity of robust evidence in terms of its superiority over VATS for peri-operative outcomes and long-term oncological adequacy is limiting its utility especially in public health care systems.

Microlobectomy—smaller incision than VATS or robotic surgery

Microlobectomy is one of a range of novel techniques currently under evaluation—created by a group of VATS lobectomists internationally and has some advantages for experienced VATS surgeons.

Firstly the technique of the lobectomy is not too dissimilar to the more usual VATS lobectomy. Our group has used this technique to perform resections of every lobe (both anterior and posterior approach) and we recommend that surgeons interested in trying this technique place their

Figure 1 Right upper lobe sleeve microlobectomy (30). Available online: http://www.asvide.com/articles/1418

5 mm ports in the usual positions. We have also performed segmentectomy and sleeve resections safely (*Figure 1*: right upper lobe sleeve microlobectomy) and a right pneumonectomy where a subxiphoid extraction was, in our view, particularly advantageous.

Our group uses CO_2 insufflation, which allows more space in the hemithorax and aids with lung collapse at the start of surgery especially in patients with air-trapping. Furthermore, the dissection and safe placement of a subxiphoid port is facilitated. Depending on surgeon preference, if, after the initial steps of the operation it becomes less useful, the CO_2 could be turned off. Of note our technique is a fully endoscopic technique and therefore forceful or uncontrolled suction may cause lung inflation. We prefer intermittent suction or the use of rolled-up tonsil-swabs to remove small amounts of blood intraoperatively.

Operative technique

The patient is intubated with single lung isolation and positioned in a standard lateral position (*Figures 2,3*). The patient should be positioned in the same position that the operating surgeon is familiar with, for their usual VATS technique. The only modification is that the xiphisternum, costal margins and the midline down to the umbilicus is marked prior to positioning. After turning into the lateral position, good access to the subxiphoid area must also be ensured (*Figure 4*).

For patients undergoing an anterior approach lobectomy, the first port is placed in the 4^{th} intercostal space between the inferior angle of the scapula and the nipple. In a normal VATS lobectomy this would be the area of the utility incision and in uniportal surgery this is the location of the single incision. For microlobectomy a 5 mm port is inserted

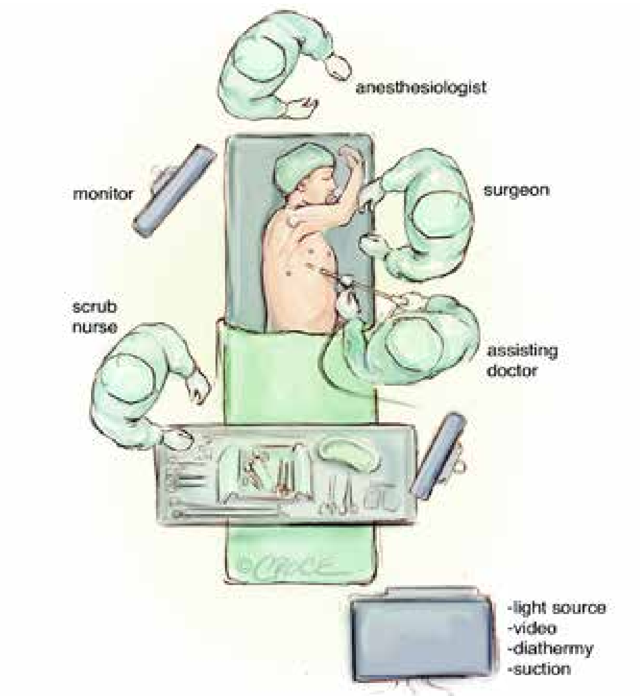

Figure 2 Theatre set up for microlobectomy (Copyright Joel Dunning).

Figure 3 Port placements for microlobectomy (Copyright Joel Dunning).

here. Chest entry is gained under vision with the Kii-Fios first-entry port (Applied Medical, California, USA) with CO_2 running at 5 litres per minute (*Figure 5*). The camera is placed in the centre of the clear plastic trocar and the port

Figure 4 Position of the subxiphoid utility incisions and the other three 5 mm ports (Copyright Joel Dunning).

Figure 5 The Kii-Fios first entry trocar.

is inserted under vision. As soon as the trocar breaches the pleura the CO_2 pushes the lung away and this can be seen endoscopically. If there are adhesions, these will be seen and the CO_2 will facilitate their separation from the chest wall.

Once the chest has been entered, the hemithorax is insufflated to a pressure of 5–10 mmHg. High CO_2 levels may cause hypercarbia, high airway pressures or hypotension so the flow rates may have to be adjusted temporarily to allow these parameters to stabilise.

The camera is then directed down to look at the inferior border of the sternum and the antero-medial diaphragm. A 20 mm skin incision is made vertically just below the xiphisternum, then under vision the soft tissue is dissected down to the tip of the xiphisternum which marks the cranial portion of the linea alba. This is incised vertically for 15 mm. It is important not to deviate into the rectus abdominis muscle as this will cause unnecessary post-operative pain. A finger is then passed cranially directly posterior to the xiphisternum and up behind the sternum as far as possible. This is similar to the move a surgeon makes prior to performing a sternotomy. The finger is then moved laterally into the hemithorax under direct vision.

Once the pleura is breached this can be followed with a 12 mm port. The diaphragm is always well below this entry point due to the CO_2, and we have not encountered any subdiaphragmatic entries with this method.

After the subxiphoid port has been placed, two further 5 mm ports are made according to the usual positioning of the surgeon's further ports. Often this corresponds to the ports described as the standardized anterior approach by Hansen and Peterson (18,19), but the operation has also been performed safely using the posterior approach (20), with the camera port first being placed posterior to the inferior border of the scapula.

The operation is then conducted in the usual fashion using 5mm instruments. Retraction can be achieved through the subxiphoid port, and stapling can either be achieved using the 5mm Dextera Microcutter for vascular structures (Dextera Inc, Redwood City, CA, USA), an energy device, or if none of these are available, a 12 mm standard stapling device can be used from the subxiphoid port. This port is conveniently located at the anterior end of the oblique fissure on both sides and thus enables good access to the hilar structures for stapling. Further information on the surgical technique and useful instruments can be found at www.microlobectomy.com.

At the end of the procedure an endo bag is placed from the subxiphoid port and then once the specimen is in the bag, under vision, the linea alba is extended as far as necessary to remove the tumour. The chest tube is inserted through the subxiphoid port and this wound is then closed, taking care to suture the linea alba under vision throughout its length to prevent an incisional hernia.

There is a wide range of novel instrumentation which facilitates minimally invasive surgery. The Covidien Single Incision Laparoscopic Surgery (SILS)® dissector is a 5 mm instrument that can articulate to 80 degrees. This is particularly useful for dissecting around vessels. The Dextera Micro Cutter® is a stapling device that has recently received FDA approval. It is licensed for the transection of vessels up to 2 mm in clamped wall thickness and is particularly useful for small segmental vessels. In addition to its narrow diameter it is also able to articulate to 80 degrees. There is now a wide range of high quality 5 mm cameras with a resolution not dissimilar to 10 mm cameras. While 3D imaging is not yet possible in 5 mm we believe that these 5 mm cameras are very versatile and suitable for anatomical lung resection. Additionally, for the sleeve resections, 5 mm endoscopic needle holders can be used (the sutures can be inserted via the subxiphoid 12 mm port).

In VATS lobectomy, safety is paramount and emergencies should be planned for. A key step in addressing significant bleeding in endoscopic lobectomy is the ability to apply pressure to the area of bleeding with a wide based swab or sponge stick. We routinely use one or two rolled tonsil swabs in the chest. Microlobectomy does not allow for the rapid insertion of a sponge stick, but we find that it is possible to grasp the tonsil swab in the chest and then apply pressure to the area of concern. An alternative method is to grasp the lung and place this over the area of bleeding. If bleeding is controlled then conversion to thoracotomy can easily be performed. We have also easily converted to the standard VATS approach in bleeding simply by extending the size of the ports and creating a utility incision, and have been then able to deal with bleeding by VATS and complete the operation endoscopically.

Adhesions are not a contraindication to microlobectomy. The CO_2 allows the separation of all but the most dense of adhesions and allows entry into the chest. As the first port has the camera in the trocar, if adhesions are seen, then a sweeping action of this port under vision is a very safe way to create some space in the chest prior to the insertion of further ports. We have yet to convert to VATS to complete the case due to adhesions.

As the operation utilizes the same view as a surgeon's usual approach, we have found that lymphadenectomy is no different to a standard VATS lobectomy. The nodes may be removed through the subxiphoid port and may be removed in a bag if they are large. The subxiphoid port is also useful for retraction for station 7. A small bag may be inserted into the chest, and retraction performed until the end of the lymphadenectomy and then the bag removed at the end of this part of the operation.

All operations have weaknesses and microlobectomy is no exception. Using the subxiphoid port for retraction rather than 2nd or 3rd instruments through the utility incision is sometimes cumbersome and some practice and experimentation with 5 mm retraction devices is required. Suboptimal retraction can lead to delays in the operation. The closed chest technique does require valved suction and brief bursts of suction, as more prolonged periods of suction does cause lung re-inflation.

So far, 72 patients have undergone microlobectomy in 6 hospitals sited in the UK, US and Denmark. A total of 40/72 of cases (55.5%) involved the upper lobes. The median operating time is 180 mins (range, 94–285 mins) and blood loss was 118 mL (range, 5–800 mL). There was a 4.1% conversion rate for bleeding and 2.8% conversion to VATS rate (by extending a port to become a traditional utility incision). The median hospital stay was 3 days (22% of patients going home on post-operative day 1). The other common complications were pneumonia (14%), prolonged air leak (7%), atrial fibrillation (4%) and prolonged intubation (4%).

Our most important weakness is that we present no evidence that microlobectomy is superior to any other endoscopic lobectomy technique or indeed to a thoracotomy. We believe that at this stage it is for individual surgeons to select their own techniques from the range available. We present this article and additional learning resources to enable surgeons to try this method as part of their own journey to find their own optimal technique. This weakness is not new and there is no compelling evidence of superiority of any other one endoscopic lobectomy technique over another currently. Indeed such is the doubt over the superiority of endoscopic lobectomy versus lobectomy by thoracotomy that there are currently several randomized controlled trials recruiting internationally including a large multi-centre randomized trial called VIOLET aiming to recruit 495 patients in the UK to answer this question (31).

Conclusions

Minimally invasive surgery has revolutionised the way we treat primary lung cancer. There are a variety of different techniques, approaches, instruments and modalities that are constantly evolving to enable safer and easier surgery; as well as to improve the patient experience not just in the immediate post-operative phase in terms of length of stay, pain and complications but also for the longer term so that adjuvant therapy can be administered as soon as possible after surgery. While the uptake of VATS or robotic surgery in the UK and EU is low, there is still some room for growth. There is a paucity of randomised control trial data to compare VATS with robotic and/or open procedures but hopefully the upcoming VIOLET study will be able to address some of these key questions. However, we know from observational data and small RCTs, VATS and robotic lobectomy is safe, feasible and reproducible.

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Footnote

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