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Review

# Robot-assisted surgery for lung cancer: State of the art and perspectives

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ABSTRACT

The robotic surgical system is the result of a long process of development aimed at producing a natural extension of the surgeon's eyes and hands via the intermediation of a computer. In this way, the ease of movement obtained with open surgery is summated with the advantages of the minimally invasive technique. Since 2000, when the first robotic system for surgery was introduced, robot-assisted thoracic surgery (RATS) has been adopted by an increasing number of centres around the world, and today is used in ∼10% of lobectomies in the US. Here, we review the characteristics and function of the robotic system available today (namely, Intuitive Surgical Inc.'s da Vinci Surgical System), outline the different techniques for major lung resection via RATS, compare RATS with video-assisted thoracoscopic surgery (VATS) and thoracotomy, and speculate on future developments. To date, no randomized trials have reported comparative data on RATS vs. VATS/thoracotomy for lung cancer. Retrospective analysis comparing RATS vs. thoracotomy have revealed advantages for the former, especially shorter hospital stays and a lower complication rate, but RATS produces similar or only slightly better results to VATS, the two being minimally invasive techniques with no need for rib separation. A few studies have reported RATS to be safer than VATS, with less conversions for bleeding, less complications; in others, it was associated with lower postoperative consumption of pain killers and quicker return of patients to normal activity. In addition, lymphnode upstaging has been shown to be higher with RATS than with VATS, with a similar rate as thoracotomy. The main disadvantage of RATS is the higher costs of instrumentation. Nevertheless, the future will probably see reductions in the costs and improvements in the instrumentation, integration with 3D imaging to improve virtual reality, and more patients benefitting from minimally invasive procedures for lung malignancies.



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## 1. Introduction

When it was introduced in the operating room in 2002, the robot-assisted approach to pulmonary resection [1,2] was considered by many thoracic surgeons a tool for privileged hospitals, on account of its high costs. Many limitations were emphasized, such as the spatial footprint of the apparatus, the complexity in installing the robot's arms into the patient's chest and the increased duration of surgery; operating at a distance from the patient was also considered a source of anxiety by many surgeons. As a result, time was needed to gain confidence with the new apparatus. Moreover, a change in surgeons' mentality was necessary before the new procedure could be accepted and embraced. Indeed, with time, surgeons increased their familiarity with the technique, the technology improved and most of the aforementioned limitations were overcome; in the meanwhile, advantages related to improved vision over the operative field, increased comfort for the surgeon and the precision of the manipulations became progressively more appreciated.

Indeed, according to the database of the Agency for Healthcare Research and Quality (AHRQ, http://hcupnet.ahrq.gov) – a US government database that collates data from small hospitals and non-academia – in 2009, 66% of lobectomies were performed via thoracotomy, 33% via video-assisted thoracoscopic surgery (VATS) and only 1% with a robotic system; In 2013, the figures were 56%, 33% and 11%, respectively. Thus, robot-assisted thoracic surgery (RATS) was being increasingly used to the detriment of open surgery, with the proportion of VATS remaining stable. The data from the highly academic Society of Thoracic Surgeons' (STS) database showed a higher growth rate for VATS compared with that obtained from the AHRQ database, indicating that academic centers were performing lobectomies more with VATS. This was confirmed by Paul et al. [3]: analysis of the lobectomies deposited in the Nationwide Inpatient Sample (NIS) database – the largest all-payer inpatient healthcare database in the US – the absolute number of RATS lobectomies, the number of centers performing RATS lobectomy and the rate of RATS vs. all lobectomies per center increased dramatically between 2008 and 2011. Between 2011 and the end of 2015, the centers performing robot-assisted lobectomies increased 90% worldwide, with the number of procedures conducted with this technology increasing 185%. By the end of 2015, market analysis reports indicated that the share of robot-assisted lobectomies in the US was ∼15%, with over 400 surgeons performing RATS. There is a feeling that robotic systems are destined to become an essential reality in the surgeon's armamentarium of the future. Here, we review the available literature on robot-assisted thoracic procedures. We analyse the evidence obtained so far in terms of comparison of RATS with manual VATS and the open-surgery approach, and describe the different surgical techniques and the current limitations of the procedure. Moreover, we imagine perspectives for the future and the possible applications of this new technology.

## 2. Description of robotic technology

The da Vinci Surgical System (Intuitive Surgical Inc., Sunnyvale, CA, USA) is the only robot available on the market for RATS. It is a tele-surgical system that consists of a robotic unit with 3/4 arms (the slaves) controlled by the surgeon via a remote console (the master). The da Vinci robot is the result of a long developmental process aimed at naturally extending the surgeon's eyes and hands, and combines the ease of motion capable in open surgery with all the advantages of a minimally invasive surgery (MIS) technique. The surgeon sits at a console some distance from the patient, who is placed on an operating table in close proximity to the robot. The console provides a magnified, high-definition (HD), three-dimensional (3D) view of the operating field via a stereo-endoscope in one of the arms. The surgeon manipulates "master" instruments on the console, and the movements are transmitted via the robot to the slave instrumentation inserted into the patient's body via small incisions. The system incorporates proprietary remote-centre technology, in which a fixed point in space is defined and about which the surgical arms move to minimize stress on the thoracic wall during manipulations. The instrument offers a wide range of high-precision movements that can be variably scaled to those of the surgeon. The master joystick perfectly reproduces the movements of the surgeon's wrist. The console consists of a screen that can display digital input from the stereo-endoscope and from ECG, CT, etc; pedals that allow the surgeon to engage and disengage different arms and reposition the master [4]; and slaves that hold the main components of the robot: the camera and the proprietary EndoWrist instrument. The last generation system, da Vinci Xi, was introduced in 2014 (Fig. 1) with simpler docking, a more user-friendly design, a "port placement" menu and laser guidance. In addition, the thoracoscope has a digital end-mounted camera with autofocus for improved vision, requires no draping and can be placed onto any of the robotic arms. Lastly, the improved design of the arms allows placement of the ports relatively close together while still avoiding collision.

## 3. Robot-assisted techniques for thoracic surgery

Three main techniques of RATS for lobectomy and segmentectomy have been described. The first – introduced by Park in 2006 – reproduces the patient and port positions of the anterior VATS approach with a utility incision of 3–4 cm in the IV intercostal space on the mid axillary line (Fig. 1), and uses two more trocars for the camera port and for the second instrument; as a result no CO2 insufflation is necessary [5], and the surgical steps reproduce those of VATS lobectomy, with anterior-to-posterior hilum isolation. This approach was modified by Veronesi et al. [6,7] during the first comparison between open, muscle-sparing thoracotomy and RATS lobectomy (four-arm technique with a 3 cm access port). This technique introduced the use of a fourth arm, positioned posteriorly, and was mainly utilized to place the lung parenchyma in the correct fixed position and obtain good exposure of the surgical field.

A similar four-arm technique was described by Cerfolio et al. [8]. They positioned the four arms along the same intercostal space (usually the 7 th), between the mid-axillary and paravertebral lines, at the minimum distance of 9 cm, with no utility incision. $CO_2$ insufflation was standardized and resections were removed within a plastic bag via enlargement of the trocar incision in the VIII i.c. space. A posterior-to-anterior approach to the hilum was described, with vein resection as the final step of the lobectomy. The results were good in terms of duration of surgery and speed of postoperative discharge.

Dylewski et al. [9] reported on 200 robotic resections using a three-arm approach in which pulmonary resection was performed only through ports with CO2-induced pneumothorax (complete portal robotic lobectomy, CPRL). At the end of the procedure, the resections were extracted via a subcostal, transdiaphragmatic approach, and the diaphragm subsequently repaired. With this technique, re-admission rate was around 10%, usually for effusion requiring drainage or post-operative pneumothorax.

Other technical variants have been described. Gharagozloo et al. [10] reported on 100 consecutive cases operated on with a hybrid, two-phase procedure: robotic isolation of hilar elements and mediastinal lymph-node dissection, followed by stapling of the hilar structures using a manual VATS approach. The complication rate was 21%, and three patients died postoperatively. The authors sug-

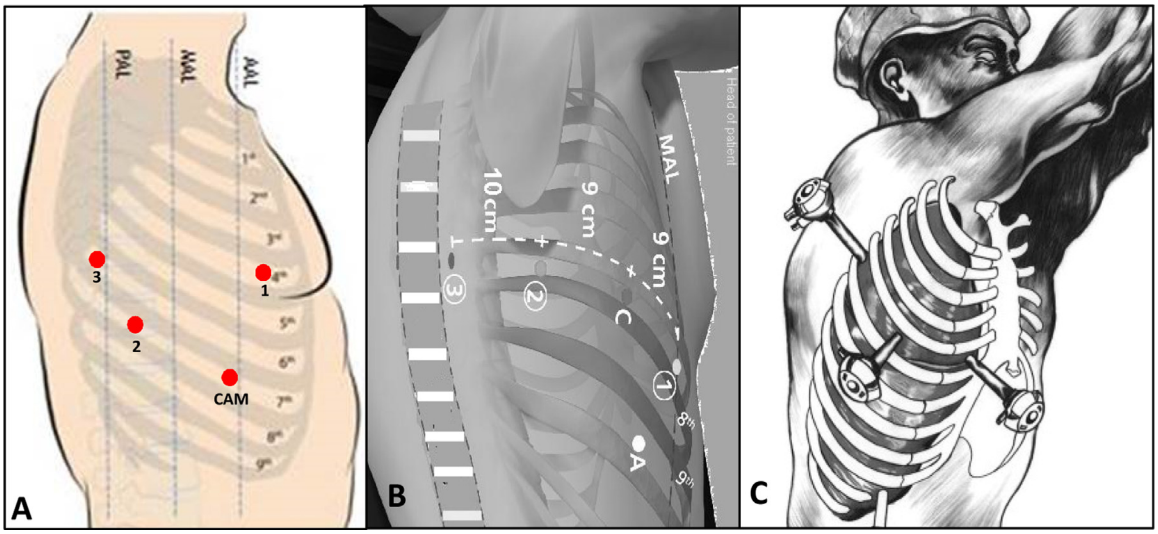


**Fig 1.** Port placement according to three different techniques for robotic lung lobectomy. (A) Park/Veronesi in New York-Milan (6); (B) Robert Cerfolio in Alabama (7); (C) Mark Dylewski in Miami (8).

gested that a robot-assisted approach was best for fine dissection of lymph nodes and vascular structures, whereas the established VATS procedure was superior for the lobectomy phase. Other authors [11,12] used a three-arm technique, with the camera placed in the 6th or 7th intercostal space along the posterior axillary line, and the other one positioned through a utility incision made at the 5th intercostal space along the submammary line.

The main advantages of using the utility port from the beginning instead of at the end of the procedure are: i) the possibility of palpating the lung and removing a specimen in the case of a diagnostic wedge resection of small nodules before lobectomy is confirmed; ii) the use of only four ports instead of five (compared with the Cerfolio technique); iii) the possibility of enlarging the same utility incision in case of conversion, avoiding an additional thoracotomy; iv) comfortable access with a sponge in the case of emergency bleeding; and v) no need for $CO_2$ insufflation. $CO_2$ insufflation, which is not routinely used in the Park/Veronesi techniques [5–7], can be used in the case of specific indications, such as obesity, relaxation of the diaphragm, incomplete lung exclusion due to air trapped in COPD patients or problems with the tracheal tube. The benefit of complete portal robotic procedures according to Cerfolio et al. [8] is avoidance of the cold 22 °C ambient air of the operating room interfering with the 37 °C temperature within the chest, preventing potential tissue desiccation and further inflammation.

## 4. Training and learning curves for robotic assisted technique

The process of gaining experience and improving skills in surgery is called the "learning curve" [13]. Many studies confirm that robot-assisted surgeons may not need prior experience with laparoscopic or thoracoscopic surgery to adapt to the system. Hernandez et al. [14] observed that the learning process with Intuitive Surgical's *da Vinci* system (Sunnyvale, CA, USA) – the only available surgical robot on the market today – is shorter than that for laparoscopic surgery. The difference between the learning curves of traditional thoracoscopy and RATS could be explained by the increased dexterity afforded by the wrist instrument, motion scaling, tremor filtration, absence of the "fulcrum effect" and increased depth perception. Often, when a thoracic surgeon sits in front of a robotic console and sees the thoracic cavity in 3D, 10× magnified view, it is easy to think that these are the advantages of robot-assisted surgery; however, improved visibility does not necessarily guarantee improved outcomes [15]. Park et al. [5] indicated that before implementation of the robotics to a clinical practice, the surgeon and operating-room team should attended an intensive, 2-day certifying course given by Intuitive Surgical Inc. Moreover, Melfi et al. [16] reported that to perform robot-assisted surgery in a safe and straightforward manner, it is necessary to standardize procedures and establish operative schemes.

The robotic apparatus requires meticulous preparation in terms of set-up and placement at the operating table. The transition from traditional surgery to advanced, totally robot-assisted surgery is not immediate. Just as in the passage from open surgery to minimally invasive surgery (MIS), precise organizational and didactic routes must be followed. Advanced training on robotic systems provides the surgeon and surgical team with confidence when operating in tiny intracavitary spaces. This allows them to activate and maintain the entire operative system, recognize and correct errors and take charge of handling all materials and instruments. Approximately 20 cases are necessary to complete adequate training. Binocular and 3D visualizations, a restricted operative field, the handling of robotic surgical tools with a joystick, positioning of the robotic arms and its instruments, and absence of tactile feedback are important aspects that the surgeon needs to become familiar with during the learning curve.

After the initial theory course, training at the console becomes the surgeon's first real contact with robot-assisted surgery. The use of a simulator is an important step in learning robot-assisted procedures. Residents and fellows must score at least 70% or higher on 14 of the 30 exercises performed on either mechanical or animal models before being able to sit at the console and operate on patients [14]. Thus, it is desirable to have a robot available exclusively for teaching purposes.

The most frequent procedure used in the initial phase of the learning curve is the treatment of mediastinum lesions (neurinomas, pericardial cysts) as Cerfolio et al. suggest [15]. These procedures represent an ideal training model because they provide the means for learning basic procedures combined with a relatively simple technique. A dual console represents an optimal training tool and greatly facilitates the process of gaining dexterity with active proctoring and reduced risks. As surgical experience grows, indications for the robotic technique can be extended to include an increasing number of more complex procedures.

Different authors [5,6,16] have reported a need of 18–20 robot-assisted lobectomies performed with the *da Vinci* apparatus for an experienced thoracic surgeon to complete the learning curve. Thus, compared with VATS lobectomy, robot-assisted surgery initially seems to require a shorter learning phase. However, a comparative study by Veronesi and Pardolesi on the learning curves of two surgeons (from the same institution and with the same thoracotomy experience) for RATS and VATS, found there were two stages with RATS: an initial decrease of operative time from 220 to 190 min after the first 20 procedures, and a second reduction to 150 min after the first 90 [17]. Thus, RATS may not necessarily have a shorter learning phase.

## 5. Comparison of robot-assisted with "open" major lung resections

Up until the last couple of decades, thoracotomy was the gold standard for the treatment of early stage lung cancer [18]. During the 1990s and 2000s, surgical technique has been refined and the global trend has led to MIS techniques [19]. Currently, the robot-assisted approach represents the most promising MIS option. However, even the most experienced minimally invasive surgeon cannot sidestep traditional open surgery. As a matter of fact, the treatment of locally advanced lung cancer (T4-vertebrae, T4-SVC) cannot avoid a thoracotomy approach [20,21]. Leading experts in the treatment of locally advanced lung cancer prefer the thoracotomy approach, which allows proper exposure of the anatomical regions concerned, ensuring conduct of surgery with the greatest possible safety. However, the MIS approach, so far reserved for clinical stage I/II lung cancer [22,23], can be expanded to select higher-stage cases thanks to the introduction of robotic technology.

The first robot-assisted lobectomy in Europe was described by Melfi et al. in 2001 [1]. Since then, technological advances have led to its widespread use on all continents [24]. Previous studies have compared classic open surgery with the minimally invasive RATS technique. Among these, we report the 5 five most important.

In 2011, Cerfolio et al. [25] published a retrospective study in which they analysed over one hundred patients undergoing pulmonary lobectomy with RATS vs. nerve-sparing rib thoracotomy: they found that RATS had lower morbidity and mortality, necessitated a shorter hospital stay, and produced better quality of life. Veronesi et al. [6] compared 54 patients undergoing RATS lobectomy vs. 54 propensity mathed open surgery: they found similar rates of postoperative complication, as well as of atrial fibrillation and air leak, but postoperative stay was shorter in RATS patients. However, RATS required more time than open surgery, though the gap decreased by the end of the learning curve. The authors concluded that RATS lobectomy for lung cancer was feasible and safe.

In 2012, the Collaborative Research (CORE) Group meta-analysed two observational studies and found fewer complications after RATS vs. thoracotomy for selected patient with early-stage non-small-cell lung carcinoma [26].

In 2014, Kent et al. [24] analysed data from the State Inpatient Databases (SID) – a US national database that includes the most important US centres – comparing the outcomes of pulmonary resection via open surgery, VATS and RATS: in an unmatched analysis, robot-assisted resection was associated with lower mortality and reduced hospital stay than thoracotomy; with a propensity-matched analysis, robot-assisted lobectomy was associated with significant reductions in mortality, length of hospital stay and overall complication rate. In summary, they concluded that resection via RATS was an appropriate alternative for MIS on the thorax, and was associated with improved outcomes compared with thoracotomy.

Park et al. [27] performed for the first time a multicentre retrospective cohort trial in 2014, using prospectively collected data from the thoracic surgery division of three major institutions. This is one of the largest reported studies on totally robot-assisted lobectomies and the first analysis of long-term outcomes in the treatment of early stage lung cancer. Overall and stage-specific survival was consistent with the largest recent series of VATS and open thoracotomy lobectomies. Five-year survival was 49% for stage II patients, 91% for stage IA patients and 88% for IB patients. However, the promising results might have been due to the small tumour size (median 2.2 cm) of the patients selected.

## 6. Comparison of robot-assisted with VATS major lung resections

Analysing the literature on pubmed, we selected eleven articles. No randomised studies are available while retrospective and case control analysis presented controversial results on benefits and limits of robotic approach compared to VATS.

Louie et al. [28] compared 52 robotic lobectomies and 32 vats lobectomies for early stage lung cancer and found a benefit in the reduction of pain, and hence of analgesic-drug use, and in an earlier return to usual activities; however, clinical outcomes were similar.

A multicentre study by Wilson et al. showed that the rate of nodal upstaging for robotic resections appears to be superior to vats and comparable to open [29].

Some clinical benefits of robotic approach compared to VATS were observed by Farivar et al. [30]. Data from consecutive robotic anatomic lung resections were collected from two institutions (n = 181) and matched for anatomic resections via thoracotomy (n = 5913) and VATS (n = 4612) from the STS National Database. There was a significant decrease in 30-day mortality and postoperative blood transfusion after robotic lung resection relative to VATS and thoracotomy. The patients stayed in the hospital 2 days less after robotic surgery than VATS and 4 days less than after thoracotomy. Robotic surgery led to fewer complications compared with thoracotomy.

The initial experience by Augustin et al. [31] was characterised by intraoperative complications that brought the authors to conclude that RATS increased the risk of bleeding and the procedural costs. Conversely other authors [32–34] did not observe any real differences in outcomes between the two techniques. Kent et al. [24] reviewed the National Database, comparing 33,095 thoracotomies with 20,238 VATS and 430 RATS: they concluded that RATS represented an appropriate alternative to VATS and was associated with improved outcome compared with thoracotomy. Swanson et al. [35] compared pulmonary resection conducted by RATS (335 lobectomies and 330 wedge resections) vs. VATS (3818 lobectomies and 11,019 wedge resections) and found differences in terms of surgical features, post-operative complications and cost-effectiveness, few clinical differences in perioperative adverse events, and that robot-assisted procedures were encumbered by increased costs and longer operative time. However, comparing wedge cases with lobectomies presented a limitation, with intrinsic differences between the two subsets most likely resulting in a bias of the study. Ye et al. [36] published a *meta*-analysis showing how robot-assisted and thoracoscopic results in the surgical treatment of early stage lung cancer were similar. However, the study did not demonstrate any superiority, nor a real clinical benefit, of one technique over the other; they concluded a need for prospective randomised studies. Finally, Mahieu et al. [37] retrospectively compared their first 28 VATS lobectomies with their first 28 RATS lobectomies. Although the sample was small, they observed that outcomes in the two groups was similar, even regarding the learning phase, but that the robot-assisted approach seemed to offer more operative safety with fewer conversions due to uncontrolled bleeding.

Recently, the long term outcome of robotic approach versus VATS and *open* has been assessed in a multicentre retrospective study [38] showing that minimally invasive approaches to lobectomy for clinical stage I NSCLC resulted in similar long-term survival but shorter length of stay as thoracotomy. Robotic approach resulted in greater lymph node assessment compared to both VATS and open approach.

The discrepancy of results available so far suggests that prospective multicentre randomized studies are necessary in order to understand whether there are real advantages of RATS over VATS that could justify the actual higher cost.

One possible advantage of the robot-assisted approach involves the treatment of locally advanced lung cancer. The commonly accepted indications for lung cancer are non-robot-assisted MIS for localized stage I–II disease [39], and thoracotomy for locally advanced disease because it guarantees radical lymph-node dissection; to date, very few papers report the results of MIS for stage III disease [38]. A potential advantage of RATS over the more traditional VATS is the increased radicality obtained with the former at the level of mediastinal lymph node stations, whereas the benefits over open thoracotomy are due to improved tolerability of surgical trauma in fragile patients when surgery is delivered after induction treatment. In the case of occult N2 disease, RATS can reduce the recovery time and the time between surgery and adjuvant treatments, and give a higher chance of receiving full doses of chemotherapeutics. In addition, a potential oncological benefit is obtained thanks to reduced immune-system activation.

A multicentre retrospective analysis on the role of RATS for N2 disease is ongoing, with promising initial results.

## 7. Cost analysis and sustainability

The main argument against RATS over VATS is increased cost. Park et al. [40] analysed relative costs of thoracotomy (n = 267), VATS (n = 87) and RATS (n = 12). Operative room times were similar; postoperative stay was 4 days with VATS and RATS vs. 6 days with open surgery; and RATS was associated with an increased cost of US$3981 over VATS, incurred almost fully on the first day. Direct costs of specialized instruments and certain disposables was US$730. However, RATS was less costly than thoracotomy (−US$3988); indeed, increased surgery and disposables costs and operation time were substantially offset by decreases in other hospital costs. However, the institution's outlay for robot-assisted technology was not added to each case through amortization. Nevertheless, upon theoretical cost-analysis, assuming a 7-year life span of the instrumentation, each case was deemed to incur an additional cost of US$857 if an average of 300 cases/year were handled. Thus, even including amortization, RATS was cheaper than thoracotomy. In contrast, an analysis by Swanson et al. [35] on 15,502 interventions (96% VATS: 4% RATS) found that RATS had higher hospital costs, longer operative times and no improvements in adverse events. Considering only lobectomies in a matched-pair analysis, RATS was ∼15% more expensive than VATS (US$21,833 vs US$18,080), but for the complications rate and hospital stay, it should be noted that 335 RATS lobectomies were performed in 40 different hospitals, equating to <8 cases/centre in 2 years. It is clear, then, that the bias in the learning curve for these robot-assisted interventions does not permit the formation of conclusions on the complications rate and cost effectiveness. Similarly, Paul et al. [3] compared the perioperative outcome and costs for robot-assisted lobectomy vs. thoracoscopic lobectomy from 2008 and 2011 (2478 RATS lobectomies and 37,595 VATS lobectomies), finding robot-assisted surgery to be unfavourable for costs and complication rate. However, also this study was biased because a greater proportion of RATS was performed in small-to-medium sized hospitals, in non-teaching hospitals and those with a moderate volume of patients.

Another study of 184 consecutive interventions (69 thoractotomies; 57 RATS; 58 VATS), on patients with similar comorbidities, found no differences in complication rates or length of hospital stay but statistically different operation times; there were no statistically significant differences in overall cost between thoracotomy and RATS (Δ US$1975) but RATS cost US$3182 more than VATS ($p < 0.001$) owing to the cost of supplies and depreciation of the robot. The authors concluded that VATS was the least expensive surgical approach, and that RATS needs to be performed with shorter operative times and/or reduced supply costs to become competitive [41].

One of the largest single-surgeon experiences in robot-assisted surgery was reported in 2014 by Nasir et al. [42]. Robot-assisted lobectomy for cancer was deemed to offer outstanding results, excellent lymph-node removal and minimal morbidity and pain. Despite the costs, it was profitable for the hospital system. Among the disadvantages, the authors mentioned the cost of the learning phase, lack of adequate time for the surgeon to become quickly proficient, and inability to palpate the lung.

Deem et al. [43] compared the outlays of lobectomy and segmentectomy, finding VATS to be the cheapest procedure in terms of procedural costs and of length of stay. On the contrary, the retrospective analysis of Dylesky et al., including 176 robotic assisted lobectomies compared to 76 VATS lobectomies (presented at CRSA, 2012), showed that robotic assisted lobectomy reduced direct cost by US$560 dollars per case as a result of reduced length of hospital stay and lower overall nursing care cost.

Of note, no published cost-analysis data are available so far for European countries. On this point, we have unpublished preliminary data indicating similar costs for RATS and VATS, all falling into the profit area in a private Hospital of the north of Italy. Indeed, the robot-assisted procedure is associated with reduced duration of hospitalizations, reduced intensity of care (in terms of postoperative exams and use of pain killers and other drugs), reduced need for transfusions and reduced stay in the intensive care unit.

## 8. Perspectives and new frontiers

The use of the robot is constantly growing throughout the world [34]. With the spread of robotic systems amongst health facilities, the number of procedures performed with this technology is growing exponentially. Robotic technology has made enormous strides to date, but in the near future we expect improvements beyond the actual use of robot-assisted surgery.

Thoracoscopic surgery is undergoing a rapid increase in the development and use of uniportal techniques [44,45]. Robot-assisted surgeons cannot avoid facing the rise of this type of procedure. Indeed, through one 4–6cm-long incision, very skilled VAT surgeons can perform a number of procedures in the chest, such as major lung resections with vascular reconstruction and lymph node dissection. This approach is becoming more and more attractive to patients as it is less invasive than traditional 3-port video-assisted surgery. As a result, robotic technologies have started to be developed towards uniportal interventions too, namely the *Single-Site da Vinci* platform in 2011. However, although this procedure provides many aspects worthy of note, to date no thoracic-surgery applications have been developed on account of technical limitations, such as the absence of compatible *EndoWrist* instruments. Sophisticated single-port robotic devices are being developed for thoracic surgery, and may be almost ready to enter the market [46]. Thus, single-port technology is being used currently only for the abdomen [47,48].

A second field of evolving research and technology is the application of fluorescence in the context of robot-assisted pulmonary surgery. In 2011, a new optical system was developed and integrated into the *da Vinci* surgical system: it is capable of emitting laser light in the near-infrared range to allow fluorescence-guided surgery thanks to the properties of the indocyanine green (ICG). ICG is a fluorescent vital dye used in medicine as an indicator agent with applications in cardiac, circulatory, hepatic and ophthalmic fields (e.g., photometric hepatic function diagnostics and fluorescence angiography). It is administered intravenously and, depending on liver performance, is eliminated from the body with a half-life of approximately 3–4 min. When injected intradermally, subcutaneously, subserosally or submucosally, ICG is drained through the network of lymphatic vessels, reaching the first lymph nodes (sentinels) in 10–20 min and then the loco-regional nodes after 1–2 h. We previously described the potential role of ICG for segmental lung resection [49], and other authors have described other applications in this area field [50–52]. In a near future, its application could be extended to the identification of mediastinal lymph nodes.

A third field of research that is being developed by Soler and Marescaux is cyber therapies. This has emerged from the development of computer and robotic sciences aimed at human–machine integration, such as the convergence of MIS, interventional endoscopy and interventional radiology into a hybrid therapeutic modality. Image-guided MIS could further extend the panel of surgical conditions potentially managed with targeted non-invasive treatments [53–57]. Image-guided hybrid MIS combines different technologies: preoperative surgical planning and simulation from personalized 3D modelling of patients, allowing practitioners to plan preoperatively the surgical intervention and choose the best treatment to apply; and intraoperatively superimposing preoperative data onto a real-world view of the patient. This augmented reality provides surgeons a view in transparency of their patient, allowing them to track instruments and improve pathology targeting by using intraoperative 3D medical-image acquisition and an associated non-rigid temporal registration algorithm. The possible future evolution of this field will be the robotization of the procedure, replacing the human gesture with a robotically automated one.

To date, only one producer has marketed a robotic system for use in clinical practice, but new robots are being developed by Medtronic and by the union of Johnson & Johnson with Google. The entry of these new instruments, hopefully along with others, into the world of robot-assisted surgery is today a highly desirable event that will undoubtedly determine the reduction of costs and, hence, permit this technique to become an option for the wider community.

## 9. Conclusions

Robot-assisted technology has indisputable technical advantages over traditional video-assisted surgery. The robotic approach combines benefits of minimally invasive surgery with precision of movements, comfort and three-dimensional views of the surgical visual field. The learning curve for robot-assisted thoracic surgery necessitates work on 20 cases, but improvements continue up to the completion of 90 cases.

According to recent studies, for early stage non-small-cell lung carcinoma, perioperative outcome appears superior after robotic (assisted surgery) when compared to open and VATS approaches, while lymph node upstaging and intraoperative safety seem to improve with RATS. Different studies show higher costs of RATS vs. VATS. The diffusion of robotics in the operating room seems destined to spread further on account of the widening of implications to include locally advanced disease, the improvements being made to the instrumentation and underlying technology, and reductions to the implementation costs.

## Conflict of interest

Giulia Veronesi is consultant for Abi medica. For other authors there are no conflicts of interest to declare.

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