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REVIEW ARTICLE

Current status of robot-assisted thoracoscopic surgery for lung cancer

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Abstract

The robotic surgical system was designed to overcome the drawbacks of conventional endoscopic surgery. Since national health insurance in Japan began covering robotic-assisted thoracoscopic surgery (RATS) for malignant lung and mediastinal tumors in 2018, the number of RATS procedures being performed domestically has increased rapidly. This review evaluates the advantages and disadvantages of RATS for patients with lung cancers, based on an electronic literature search of PubMed. The main advantages of RATS are its ability to achieve excellent lymph-node removal with low morbidity and mortality, and minimal postoperative pain. Conversely, its disadvantages include a long operation time and the need for specialized instruments. However, the learning curve for RATS is reported to be shorter than that for VATS: some studies recommend that a surgeon needs to perform 18–22 robotic operations to attain sufficient skill. RATS for lung cancer is more expensive than VATS and the cost of training is high. Although the main disadvantage of RATS is that it reduces operator's tactile senses, the endoscope, which is directly manipulated by the surgeon at the console, using various magnifications, and 3D HD images on the monitor, may compensate for this. Ultimately, RATS offers better maneuverability, accuracy, and stability over VATS.

Keywords Lung cancer · Lobectomy · Robot · Thoracoscopic surgery

Introduction

The robotic surgical system is expected to compensate for the drawbacks of conventional endoscopic surgery. With technological advances, surgical approaches for thoracic diseases have evolved from thoracotomy to endoscopic surgery such as video-assisted thoracoscopic surgery (VATS) and recently, robotic-assisted thoracoscopic surgery (RATS). In 2009, the da Vinci® robotic surgical system (Intuitive Surgical, Sunnyvale, CA, USA) was introduced worldwide, but predominantly in the United States. It was subsequently granted approval based on the Pharmaceutical Affairs Law in Japan and used mainly in university hospitals [1].

In Japan, the national health insurance started to cover robot-assisted surgery for total prostatectomy in 2012. RATS for malignant lung tumors, benign mediastinal tumors, and malignant mediastinal tumors has been covered by the national health insurance since 2018; hence, the number of domestic robotic surgical procedures is increasing.

In addition to being minimally invasive, the da Vinci® surgical system has other advantages such as allowing surgeons to use intuitive maneuvers, providing wide visibility by high image-quality three-dimensional (3D) images, and enabling complicated operations to be performed with delicate instruments. Compared with VATS, which requires long straight instruments, the da Vinci® surgical system provides surgeons with greater instrument maneuverability and a wider range of motion [2].

Several studies have used stereoscopic endoscopic video to obtain better images than those obtained with monocular endoscopic video [1, 3, 4]. Although conventional VATS refers to a two-dimensional (2D) image on a monitor, thoracic surgeons derive 3D structures from their experience. In the da Vinci® surgical system, clear 3D-image information can be obtained by a 3D high-vision camera. Operational maneuvers become clearer and easier under a 3D-visual field, the surgical learning curve is shorter, and uncomplicated operations can be performed relatively promptly [4].

This review evaluates the advantages and disadvantages of RATS for patients with lung cancers.

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Methods

Literature research

An electronic literature search of PubMed was performed by entering the combination of key words (LUNG CANCER) and (LOBECTOMY) and (ROBOT) and (MORTALITY or MORBIDITY or HOSPITAL STAY or COST). The final search was conducted on November, 2018. References in selected papers were also screened to identify additional publications that might not have been retrieved from the database search. Case reports were excluded. Only RATS-related articles written in English were selected.

Feasibility and safety of RATS

Current RATS techniques have several variations in the number of robot arms, the use of CO_2 insufflation, additional utility incisions, and the locations of ports [5–9]. Furthermore, there is a report on a hybrid method consisting of two phases: robot dissection and VATS lobectomy. We perform RATS lobectomy with four port incisions and a 3-cm utility thoracotomy or CO_2 insufflation combined assistant port (Table 1), inserting a robot stapler through a 12-mm port (Fig. 1a, b).

Nakamura et al. [10] analyzed the initial 112 cases of RATS in Japan and found that RATS had been introduced safely, with a low incidence of postoperative complications

Table 1 Summary of the perioperative results in publications on robot-assisted lung resections

	First Author	Year	Cases (n)	Op time (min)	Conversion (%)	LOS* (day)	Morbidity (%)	Mortality (%)
1	Park BJ	2006	34	218	12	5	26	0
2	Melfi FM	2008	107	220	9	10	9	1
3	Gharagozloo F	2009	100	216	1	4	21	3
4	Veronesi G	2010	54	238	13	5	20	0
5	Giulianotti PC	2010	38	209	16	10	11	3
6	Dylewski MR	2011	200	90	2	3	26	2
7	Jang HJ	2011	40	240	0	6	10	0
8	Cerfolio RJ	2011	119	132	10	2	27	0
9	Hernandez JM	2012	20	203	10	3	20	0
10	Louie BE	2012	46	213	2	4	43	0
11	Nakamura H	2014	60	285	3	11	7	0
12	Deen SA	2014	57	223	–	5	32	0
13	Mungo B	2016	53	–	13	5	4	0
14	Novellis P	2018	23	150	9	4	35	4
15	Huang J	2018	389	92	1	5	9	0

**LOS* length of stay

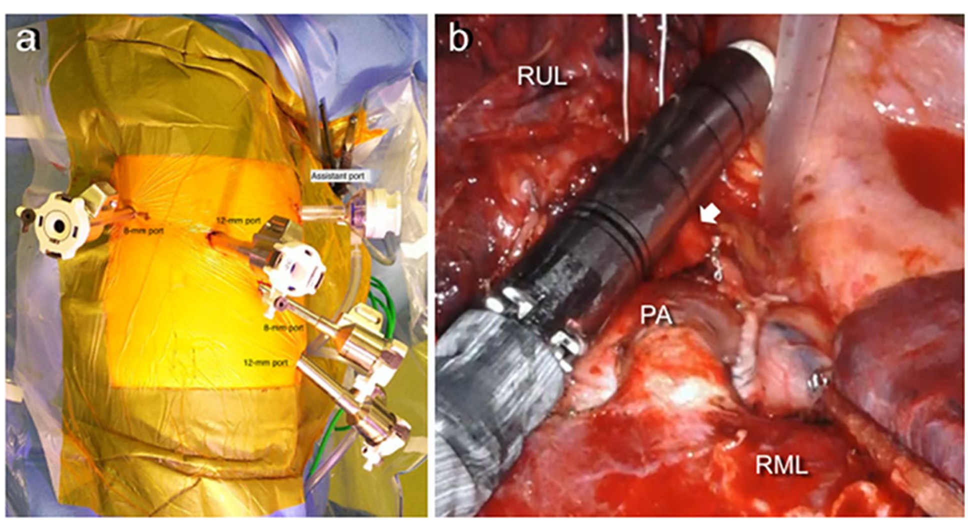

Fig. 1 Intraoperative view of port placement for robotic right lobectomy using four arms. **a** The patient's head is at the top of the picture, and the anterior chest is on the right. The four ports are placed in the same eighth intercostal space. CO_2 insufflation combined with the assistant port was standardized in the *V* intercostal space. **b** Intraoperative view of the vascular robot stapler through a 12-mm port. *RUL* right upper lobe, *RML* right middle lobe, *PA* right pulmonary artery, white arrow, the truncus anterior (the 1st branch of the right pulmonary artery)

and no operation-related mortality. The incidences of complications of VATS and RATS were 16.9% and 6.5%, respectively, being lower after RATS than VATS in Japan. They concluded that RATS will reduce postoperative complications, improve the QOL, and give superior operability for lymph node dissection in lung cancer surgery. In comparing the 40 cases of RATS for lung cancer and the 40 initial cases of VATS, RATS had a lower incidence of postoperative complications, less intraoperative blood loss, and required fewer days in hospital postoperatively [11]. In another report, comparing the outcomes of RATS and VATS in a case–control study, patients who underwent RATSs needed less analgesia and returned to their daily living activities earlier [12]. Veronesi [13] and Louie et al. [14] found that RATS for lung cancer was equivalent to VATS in curability and safety, and superior in operability. Kent et al. [15] reported that RATS was more favorable than thoracotomy and equivalent to VATS with regard to the mortality, morbidity, and length of hospital stay. Because thoracic surgeons can perform RATS safely, it is an appropriate alternative to VATS with better outcomes than open thoracotomy. Nasir et al. [16] reported that robotic anatomic lung resection is safe because RATS achieves excellent lymph-node removal, with low morbidity and mortality and minimal pain. RATS anatomic lung resection was performed for 394 patients, with conversion to open thoracotomy in 41 (10.4%), median blood loss of 20 mL, median hospital stay of 2 days, and 30-day and 90-day operative mortality of 0.25% and 0.5%, respectively. They noted that the rate of conversion decreased to 6% in the last 100 RATS cases.

Nakamura et al. [17] found that the rate of conversion to open thoracotomy was 1.0%–19.2%. The reasons for the conversion were as follows: incomplete intralobular fissure, pleural adhesion, and prolonged operative time. Other reported reasons for conversion include calcified lymph nodes on the pulmonary artery or bronchus, a tumor crossing the fissure, an adequate margin difficulty, and chest wall invasion [18]. Contrary to expectations, bleeding has been a rare cause of conversion to thoracotomy [7, 17]. On the other hand, the operative time is often prolonged [5, 7], partly because the operation is performed with maximal caution and also because the robot arm setting and exchanges of forceps require time. Veronesi [19] states that in addition to the longer operation time, the need for specialized instruments is also a disadvantage.

Concerning lymph node dissection, multiple studies show the effectiveness of RATS for lymph node dissection [14, 18]. The accomplished degree of lymph node dissection is a predictive factor for local recurrence and many authors report that the number of lymph nodes removed by RATS is similar to that removed by open thoracotomy [5, 19]. Mungo et al. [20] and Novellis et al. [21] reported that lymph nodal retrieval is significantly higher in RATS than in VATS. According to one meta-analysis, the number of retrieved lymph-node stations by RATS and VATS was 4.978 and 4.323, respectively, with no significant difference between the techniques [22]. For advanced lung cancer such as occult N2 disease, RATS could allow for quicker recovery as well as improved compliance with adjuvant treatments following surgery [23]. These authors concluded that robotic technology supports a more radical resection of complex locally advanced tumors. Moreover, several reports note less postoperative pain after RATS than VATS [10, 12, 24]. Cerfolio et al. [24] reported that a lower 3-week postoperative pain score prompted surgeons to favor RATS. Louie et al. [12] also reported that less postoperative pain was a benefit of RATS.

RATS learning curve

The fact that the learning curve for RATS is shorter than that for traditional and minimally invasive techniques is another advantage of this technology. Many studies have found that the learning curve for robotic-assisted surgery, including the steep learning curve for RATS, is superior to that for VATS because of the more intuitive movements by improved ergonomics, greater flexibility, and 3D high-definition (HD) vision of RATS (Table 2) [5, 15–18]. The main disadvantage of RATS is the reduced tactile senses of the operator. The main advantages of RATS over VATS are its easily maneuverable endoscope, manipulated directly by surgeons at the console using various magnifications, and its HD stereoscopic images on the monitor, which may compensate for the absence of haptic feedback. Storz et al. [1] demonstrated that the significant benefit of RATS is its 3D images, which allow surgeons to work faster under 3D HD visualization instead of 2D HD visualization.

Park et al. [5] reported that the operation times of eight of their ten most recent patients were shorter than the median of their total 30-patient cohort, suggesting that the completion of 20 cases is required allow the learning curve to become steeper. Other studies recommend the experience of at least 20 robotic operation cases for obtaining sufficient skill. Different studies similarly report the need for 18–22 RATS lobectomies to complete the learning curve of an experienced thoracic surgeon [25–32]. In an analysis of the operative time of 101 patients, Arnold reported that the learning curve for RATS lobectomy was 22 cases, with mastery achieved after 63 [32]. Gharagozloo et al. [8] analyzed 100 consecutive patients divided into two groups: the first 20 and the last 80, and found that the first 20 had longer operating times and hospitalization. Although the incidence of complications was similar in the two groups, the three deaths were all in the first group.

Many studies confirm that surgeons may need no prior experience of performing endoscopic surgery to master a

Table 2 Review of research studies on robot-assisted thoracoscopic surgery (RATS) lung resections based on the number of cases evaluated

	First author	Year	Question	Patients	Findings
1	Park BJ	2006	What was the initial experience of developing an approach for assessing the feasibility of the da Vinci surgical system to perform VATS* lobectomy?	34 Consecutive patients (13 men and 21 women; median age, 69 years) underwent robot-assisted VATS lobectomy with the da Vinci® surgical system	Robot assistance for video-assisted thoracic surgical lobectomy is feasible and safe The operative times of eight of the final ten patients were less than the median of the total 30-patient cohort
2	Melfi F	2008	Are there any disadvantages of da Vinci systems?	107 Low-risk patients (32 women and 75 men; mean age, 64 years) who underwent video robot lobectomy	Robotic instrumentation is still evolving The operative time is considerably longer than that of standard open surgery or VATS, but it could decrease with experience
3	Gharagozloo F	2009	What is the feasibility of robotic mediastinal, hilar, and vascular dissections during VATS lobectomy for early stage lung cancer?	100 Patients (58 women and 42 men; mean age, 65 years) who underwent VATS lobectomies with robotic vascular and mediastinal dissections	1. The patients were divided into two groups: the first 20 patients and the last 80 patients. The last 80 patients had shorter operating times and hospitalization 2. All 3 deaths were only among the first 20 patients 3. The learning curve for the use of robotics is steep
4	Cerfolio RJ	2011	Is it necessary to start a robotic program in thoracic surgery?	150 Patients (76 women and 74 men) who underwent robotic operations	The learning curve, which shows the duration necessary for surgeons to be comfortable performing the whole operation, is steep
5	Veronesi G	2011	How can we identify a learning curve for robotic pulmonary lobectomy?	91 Patients (24 women and 67 men) who underwent robotic lobectomy	1. The median duration of the operation was 239 min (range 85–411 min), being 260 min for the first 18 patients, and 221 min for the subsequent 73 patients ($p = 0.01$) 2. Inspection of the operating time curve indicates that the operating time decreased to a plateau after about 20 operations 3. Approximately 20 operations are required for a surgeon to experience major thoracic open resections, but not VATS lobectomy, for achieving competency in robotic lobectomy
6	Meyer M	2012	Can the learning curve of robotic lobectomy be defined?	185 Consecutive patients (113 women and 72 men; mean age, 65 years) who underwent robotic lobectomy	The mean cumulative learning curves for operative time, mortality, and surgeon comfort are 18 ± 3 cases
7	Hernandez JM	2012	What is the most effective way to "flatten" the learning curve?	20 Patients (13 women and 7 men; mean age, 69 years) who underwent robotic-assisted lobe resections	1. The perception that robotic pulmonary resection involves a steep learning curve may not be universally accurate 2. By implementing a robotics program, the operative times are minimized, and the learning curve associated with robotic-assisted lobectomy is "flattened"

**VATS* video-assisted thoracoscopic surgery robot-assisted operation system [5, 12–15, 19, 28]. Cerfolio et al. [26] concluded that the RATS learning curve is steep and approximately 1 year is necessary for a surgeon who wants to step up from thoracotomy to minimally invasive surgery such as RATS. Rather, to perform safe RATS, a certifying course should be required before the implementation of robotics to a clinical practice. Simultaneously, the procedures should be standardized and the operative schemes should be established [6, 27].

Other studies conclude that surgeons performing RATS lobectomy should have extensive experience in lobectomy with VATS. Therefore, Meyer et al. [28] concluded that the learning curve may be steeper for surgeons who want to move from lobectomy by thoracotomy to the robotic technique. Conversely, Hernandez et al. [29] compiled data prospectively from a consecutive cohort of their first 20 patients who underwent RATS and reviewed the results. For surgeons experienced in open and VATS lobectomy, the steep portion of the learning curve correlated with rapid learning and ended with the surgeon attaining proficiency. Following the plateau on the learning curve, no further improvements were noted, irrespective of the number of additional cases accumulated. They concluded that experience in both open surgery and VATS is useful for attaining proficiency in RATS.

Cost analysis of RATS

The main argument against RATS vs VATS is its higher cost (Table 3). Many studies report that robotic surgery is more expensive than VATS or open surgery for lung cancer [33–37]. The da Vinci® surgical system is still only a surgical robot. Novellis et al. [21] reported that in addition to a new da Vinci® surgical system, which generally costs approximately 2 million US dollars, the maintenance costs about 10% of the initial capital expenditure and expendable items such as the dedicated instruments are also expensive. The latest da Vinci® surgical system is even more expensive and the surgeons' training cost is also high. Wei et al. [33] concluded the overall hospital cost for RATS lobectomy requires an additional $3000 to $5000 per case vs VATS lobectomy. Similarly, Park et al. [34] analyzed the relative costs of thoracotomy ($n=269$), VATS ($n=87$), and RATS ($n=12$), and found that RATS required an extra US$3981 over VATS. In 15,502 interventions (96% VATS and 4% RATS), Swanson et al. [35] also noted that RATS required a higher hospital cost, and in spite of only lobectomies in a matched-pair analysis, RATS was approximately 15% more expensive than VATS (US$21,833 vs US$18,080). Paul et al. [36] compared the costs of RATS lobectomy and VATS lobectomy from 2008 to 2011 (2478 RATS lobectomies and 37,595 VATS lobectomies), and found that robot-assisted surgery incurred extra cost. Deen et al. [37] analyzed 184 consecutive interventions (69 thoractomies, 57 RATS, and 58 VATS), and found that RATS cases cost $3182, being significantly more than that of VATS, but noted that the RATS cost included the robotic-specific supplies and depreciation.

The limited data on RATS also indicate that hospitals could make a profit from robotic thoracic surgery because the operating costs of RATS seem to be lower than the reimbursement from the paying bodies. Dylewski et al. [38] reported that RATS lobectomies reduce the direct cost of each case by US$560 because of the shorter hospital stay and lower overall nursing care cost. Nakamura et al. [17] reported that a specific number of RATS surgeries should be performed to reduce its costs. Kajiwara et al. [39] calculated that at least 150–300 RATS cases a year are necessary for preventing a deficit in income in a given institution.

Discussion

Since the first report of minimally invasive lobectomy by VATS in the early 1990s, VATS has become widely accepted for certain indications [40]. VATS lobectomy is now performed routinely, but remains a controversial surgical technique. Because of the technical challenges of VATS, with its steep learning curve, many thoracic surgeons still prefer to perform open thoracotomy for pulmonary lobectomy.

In 2011, the Lancet published a report titled "From 2D to 3D: the future of surgery?", which concludes that 3D images play a massive role for real 3D space in the future of surgery [3]. Technical shortcomings in conventional VATS instrumentation have resulted in many compromises. One of the limitations of VATS is that it must be performed with non-ergonomic stiff instruments in a rigid chest cavity while watching 2D images on the video monitor. Thus, RATS has been proposed as an alternative to VATS. The da Vinci® surgical system has several remarkable improvements such as 3D HD magnification of the surgical field and tremor filtration. In particular, the instruments provide motion with 7-degrees-of-freedom, and the range of movement goes even beyond that of the human hand. Since the robotic surgical system in thoracic surgery was introduced, more than 15 years ago, RATS has been gaining popularity in many countries. Because our national health insurance started covering RATS from the fiscal 2018 year, the number of robotic thoracic surgery has been increasing rapidly in Japan. For surgeons with experience of transitioning from open thoracotomy to VATS, the evolution towards new technology including a robotic surgical system no longer incurs technical problems, as long as they are engaged and there are a sufficient number of patients.

Several comparative studies agree that RATS requires a longer operative time and the total hospital costs are higher, but both morbidity and the length of stay are lower than

Table 3 Research studies reviewing the costs of robot-assisted lung resections

	First author	Year	Comparing cost with VATS* lobectomy	Author's opinions
1	Park BJ	2008	Use of robotic technology during VATS lobectomy is associated with an average increase in cost of an additional $3981	The cost of robotic lobectomy is still lower than that of thoracotomy lobectomy by $3988
2	Dylewski MR	2012	Lobectomies performed by a robotic-assisted approach reduce the direct cost by $560 per case	The majority of cost savings are achieved by the results of reduced length of hospital stay and lower overall nursing care costs
3	Swanson SJ	2014	An ordinary least squares cost model reveals that the cost of RATS lobectomy is significantly higher than that of VATS lobectomy ($30,365 vs $20,238) and that of RATS wedge resection is also higher than that of VATS wedge resection ($27,969 vs $17,887)	RATS lobectomy and wedge resection seem to incur higher hospital costs and longer operating time, without any differences in adverse events
4	Paul S	2014	Robotic-assisted lobectomy cost is significantly higher than the thoracoscopic procedure cost ($22,582 vs $17,874)	Robotic-assisted lobectomy cost is related to higher indirect costs from the use of robotic disposable equipment and possibly longer operative times
5	Deen SA	2014	Robotic surgery cost $3182 more than VATS because of the cost of robotic-specific supplies and depreciation	1. The overall costs of open thoracotomy and VATS are similar to those of open and robotic surgery 2. The procedure-specific costs of the robotic group were similar to those of the VATS group 3. Reducing operating time, eradicating unnecessary laboratory work, and minimizing the intensive-care-unit stay will help to reduce the direct hospital costs of anatomical lung resection
6	Wei B	2016	The cost of robotic pulmonary lobectomy increases from $3000 to $5000 per case	Robotic lobectomy continues to show an estimated median profit margin of around $3500 per patient

**VATS* video-assisted thoracoscopic surgery, *RATS* robot-assisted thoracoscopic surgery

those of open thoracotomy and VATS [5–7, 10–15, 20–25], and it can be performed safely and reliably. For the safe transition from VATS to RATS, Wei et al. [33] emphasized that team training, familiarity with the instruments, troubleshooting, and preparation are critical. Cerfolio et al. [26, 27] stated that observational experience is the first important step. An inexperienced team should observe what an experienced team performs in a few robotic operations, and the inexperience team can then understand why teamwork is important in a robotic operation. Others reported that one of the most important differences between RATS and VATS is that the former requires a new set of manuals and good eye-hand coordination skills [6]. According to the report of Park et al. [5], the efforts of medical staff, including operating-room nurses and technicians, anesthesiologists, and surgical staff, are indispensable for shortening the operative time.

In addition to its longer operative time, Veronesi [13, 18] pointed out that the specialized instruments required are a disadvantage of RATS. The conventional da Vinci® surgical system with the S™ and Si™ robot requires a bedside surgeon who staples the hilar structures and separates the lungs. During sectioning of the vascular and bronchial structures, the introduction and firing of mechanical staplers is usually performed by the bedside surgeon, resulting in a longer maneuver time. Now, the da Vinci® Xi™ system, which uses a vascular robot stapler, can staple the pulmonary vessels easily. The vascular robot stapler will reduce the operative time.

Although the main disadvantage of RATS is reducing operator's tactile senses, the endoscope, which is directly manipulated by the surgeon at the console, using various magnifications and 3D HD images on the monitor, may compensate for the absence of haptic feedback [8, 18]. Robotic surgery offers better maneuverability, accuracy, and stability over VATS, and also provides surgeons with excellent instrument maneuverability and an added range of motion, which can never obtained in VATS [5–7, 25, 41–43]. Louie et al. [14] and Veronesi et al. [23] both demonstrated that RATS lobectomy facilitates hilar and mediastinal nodal dissection, deeply and accurately. Veronesi et al. [23] concluded that robotic lobectomy is feasible, safe, and oncologically efficient. Gharagozloo et al. [41] reported that the pathological status improved in 16% of their patients who underwent RATS lobectomy. In another study, Veronesi et al. [44] analyzed, retrospectively, 223 patients who underwent RATS lobectomy. N2 disease was diagnosed preoperatively in 72 (32%) patients and intraoperatively in 151 (68%) patients. Of the 223 patients, 140 (63%) received postoperative treatment and 49 (22%) underwent surgery only. Local recurrence developed in 19 (8.5%) patients. They concluded that RATS lobectomy is safe and effective for patients with Stage III non-small-cell lung cancer (NSCLC) or carcinoid tumors, and that survival of patients with NSCLC treated with RATS was similar to that of patients treated with open surgery. Since there are so few reports, long-term studies are necessary to evaluate the efficacy of RATS for advanced lung cancer [14, 23, 45]. There is data to support minimally invasive surgery [46]. Demmy et al. [46] analyzed, retrospectively, published research articles that provided adequate long-term survival data and documented oncologic concerns with VATS. Although the technical inadequacies for minimally invasive lobectomy (MIL) should be amplified for advanced cancer resections, early reports show no such concern. The report emphasizes that MIL as an oncologically equivalent operation is acceptable, with substantially lower morbidity, especially in frail populations. Furthermore, the report reasonably suggests that MIL should be the technique of choice, even as a quality indicator instructing lobectomy.

I agree with Suda's [42] conclusion that robotic surgery, which overcomes the weaknesses of conventional VATS, could ultimately soon replace VATS.

Compliance with ethical standards

Conflict of interest I have no conflicts of interest to declare.

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