Review

Robotic versus open and video-assisted thoracoscopic surgery approaches for lobectomy

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Abstract

More and more data are available on the benefits of minimally invasive thoracic surgery compared to open thoracic surgery in the curative treatment of early-stage non-small cell lung cancer. However, results are conflicting, especially when video-assisted thoracoscopic surgery (VATS) is compared to robotic-assisted thoracoscopic surgery (RATS) for lobectomy. Our goal is to report the main results of recent systematic reviews and meta-analyses comparing RATS, VATS, and open surgery for lobectomy. Using PubMed database, we selected systematic reviews and meta-analyses, which compared the short-term outcomes of patients treated by RATS, VATS, or open surgery for lobectomy. In all but one of the systematic reviews, robotic lobectomy allowed similar short-term outcomes as VATS lobectomy and better short-term outcomes than open surgery. One meta-analysis by O'Sullivan *et al.* found that robotic lobectomy was associated with fewer adverse events ($P < 0.00001$) and lower 30-day mortality ($P = 0.001$), compared to VATS lobectomy. Robotic lobectomy could be a valid alternative to VATS and open lobectomy. Short-term outcomes do not appear to be different between VATS and RATS cohorts, except in one recent meta-analysis, which reported the superiority of RATS compared to VATS. Without cost analysis and randomized controlled trials with long-term outcomes, no strong conclusions can be drawn.

Keywords: Minimally invasive surgery, robotic surgery, robotic-assisted thoracoscopic surgery, video-assisted thoracoscopic surgery, lobectomy, lung cancer, short-term outcomes, review

INTRODUCTION

Surgery is the cornerstone of early stage non-small cell lung cancer (NSCLC) treatment, and lobectomy is currently the preferred type of lung resection for clinical stages I and II of NSCLC[1]. Minimally invasive approaches, namely video-assisted thoracoscopic surgery (VATS) and robotic-assisted thoracoscopic surgery (RATS), are preferred for early stage NSCLC, and are even recommended for those early stage NSCLC[2]. Robotic thoracic surgery has developed rapidly since the first publication by Melfi *et al.*[3] in 2002, which reported the first cases of robotic thoracic procedures including five lobectomies.

Thoracic surgery approaches have evolved during the last two decades, as has the way of performing lung lobectomy, but not its goal. Lobectomy for NSCLC involves two steps, namely lung resection and complete lymph node resection, according to international recommendations[1,4-12]. Minimally invasive surgery provides better short-term outcomes compared to open surgery, with fewer adverse events and shorter length of hospital stay[13-15]. Until recently, many systematic reviews with meta-analyses and large retrospective databases comparing VATS and RATS lobectomy have provided conflicting results regarding short-term outcomes.

Our goal in this mini-review is to report the main results of recent systematic reviews and meta-analyses comparing the short-term outcomes of patients treated by RATS, VATS, or open surgery for lobectomy.

METHODS

PubMed and Web of Science were searched to identify potentially eligible literature up to 1 October 2019 reporting lobectomy performed by open surgery, VATS, or RATS and to collect data on the short-term outcomes of patients according to each surgical approach. The search items were: "video-assisted thoracoscopic surgery" OR "VATS", "robotic-assisted thoracoscopic surgery" OR "RATS", "thoracotomy", "lobectomy", "lung cancer", "techniques", "systematic review" AND "meta-analysis", AND "national database". Only articles in English language were included.

RESULTS

Performing lobectomy: common points and differences between RATS, VATS, and open thoracotomy

With the advent and the spread of minimally invasive surgery, such as VATS and RATS, the use of open thoracotomy as the "gold standard approach" has decreased. Thoracotomy includes two approaches: anterolateral thoracotomy and posterolateral thoracotomy. With both approaches, whenever possible, a muscle sparing incision is made. To perform lobectomy for NSCLC, a hilar dissection or a fissureless technique is used. Mediastinal lymph node dissection is done before or after lobectomy. Thoracotomy is still the main approach to perform lobectomy for early stage NSCLC: between 2010 and 2012, 67% of lobectomies were performed by open thoracotomy, 26% by VATS, and 7% by RATS, as registered in the USA nationwide cancer database[16].

VATS for early stage NSCLC is now well accepted, with better short-term outcomes[17,18] [Table 1]. With VATS, a fissureless technique is preferred and mediastinal lymph node dissection is done at the end of the procedure. Despite the benefits associated with VATS lobectomy, this approach is not universally used for many reasons. The main reason is the technical difficulty in performing complete hilar, lobar, interlobar, and mediastinal lymph node resection[19] according to international recommendations.

RATS offers some advantages compared to VATS. First, structures are magnified with a stable, high-quality 3D optical instrument directed by the surgeon and not by the surgeon's assistant. Instruments have up to seven degrees of freedom due to the Endowrist system. With RATS, lobectomy adheres to oncologic

Table 1. Main reports concerning short-term outcomes after lobectomy performed by thoracotomy or a minimally invasive approach as VATS or RATS for a NSCLC in studies used for this article

Ref.	Population study	Outcomes	Results
Ng *et al*.[13]	Comparison of multiport and uniport VATS and RATS 145 studies, 369,793 patients Comparison of VATS to Open: 115 studies	VATS *vs*. Open Nodal upstaging Complications 90-day mortality Length of hospital stay 5-year OS 5-year DFS VATS *vs*. RATS Nodal upstaging Complications 30-day mortality Length of hospital stay 5-year OS 5-year DFS	OR 0.71 (95%CI 0.58-0.87) $P < 0.001$ OR 0.64 (95%CI 0.59-0.71) $P < 0.001$ OR 0.78 (95%CI 0.56-1.07) $P = 0.12$ -1.9 d (95%CI -2.25 to -1.54) $P < 0.001$ OR 1.35 (95%CI 1.17-1.56) $P < 0.0001$ OR 1.15 (95%CI 0.94-1.4) $P = 0.18$ OR 1.02 (95%CI 0.85-1.22) $P = 0.87$ OR 1.28 (95%CI 0.75-2.17) $P = 0.37$ OR 1.04 (95%CI 0.73-1.47) $P = 0.85$ -0.16 d (95%CI -0.81 to -0.48) $P = 0.62$ OR 0.79 (95%CI 0.47-1.33) $P = 0.38$ OR 0.71 (95%CI 0.44-1.14) $P = 0.16$
O'Sullivan *et al*.[14]	Comparison of short-term outcomes after lobectomy performed by Open. VATS or RATS 112,356 patients	RATS *vs*. Open Complications 30-day mortality Length of hospital stay Operative time RATS *vs*. VATS 30-day mortality Operative time	OR 0.67 (95%CI 0.58-0.76) $P < 0.00001$ 0.53 (95%CI 0.33-0.85) $P = 0.08$ WMD -1.4 (95%CI -1.96 to -0.85) $P < 0.00001$ WMD 65.56 (95%CI 53.66-77.46) $P < 0.00001$ OR 0.61 (95%CI 0.45-0.83) $P = 0.001$ WMD 4.98 (95%CI 2.61-7.36) $P < 0.001$
Adams *et al*.[29]	Comparison of short-term outcomes after a lobectomy RATS to VATS and Open in a national Database n = 116 RATS n = 4612 VATS n = 5913 Open	RATS *vs*. Open Operative time Postoperative blood transfusion Air leak > 5 days Chest tube duration Length of hospital stay 30-day mortality RATS *vs*. VATS Operative time Postoperative blood transfusion Air leak > 5 days Chest tube duration Length of hospital stay 30-day mortality	241 min *vs*. 175 min, $P < 0.001$ 0.9% *vs*. 7.8%, $P = 0.002$ in % of patient 5.2% *vs*. 10.8%, $P = 0.05$ 3.2 days *vs*. 4.8 days, $P < 0.001$ 4.7 days *vs*. 7.3 days, $P < 0.001$ in median 0% *vs*. 2.2%, $P = 0.18$ 241 min *vs*. 179 min, $P < 0.001$ 0.9% *vs*. 3.8%, $P = 0.13$ in % of patient 5.2% *vs*. 8.9%, $P = 0.17$ 3.2 days *vs*. 3.7 days, $P = 0.18$ 4.7 days *vs*. 5.3 days, $P = 0.07$ 0% *vs*. 1%, $P = 0.63$
Agzarian *et al*.[30]	Comparison of short-term outcomes after a lobectomy RATS to VATS and Open 20 articles	RATS *vs*. Open Operative time Length of hospital stay RATS *vs*. VATS Operative time Length of hospital stay	WMD 40.10 (95%CI -50.76 to -130.96) $P = 0.39$ -1.97 days (95%CI -4.05 to -0.1) $P = 0.06$ in median WMD 64.28 (95%CI -50.35 to -178.91) $P = 0.27$ -0.68 days (95%CI -1.52 to -0.16) $P = 0.11$
Kent *et al*.[15]	Comparison of short-term outcomes after a lobectomy RATS to VATS and Open in a national database n = 411 RATS n = 1233 VATS n = 1233 Open for propensity-matched analysis	RATS *vs*. Open Complication rate Mortality rate Length of hospital stay RATS *vs*. VATS Complication rate Mortality Length of stay	43.8% *vs*. 54.1%, $P = 0.003$ 0.2% *vs*. 2%, $P = 0.016$ 5.9 days *vs*. 8.2 days, $P < 0.0001$ in median 43.8% *vs*. 45.3%, $P = 0.674$ 0.2% *vs*. 1.1%, $P = 0.122$ 5.9 days *vs*. 6.3 days, $P = 0.454$
Rajaram *et al*.[31]	Comparison of short-term outcomes after a lobectomy RATS to VATS and Open in a national database n = 3238 to 3689 RATS n = 3401 to 3689 VATS n = 3405 to 3689 Open for propensity-matched analysis	RATS *vs*. Open Length of hospital stay 90-day Mortality 30-day unplanned readmission RATS *vs*. VATS Length of hospital stay 90-day Mortality 30-day unplanned readmission	6.1 days *vs*. 5.7 days, $P < 0.001$ in median 3% *vs*. 3.4%, $P = 0.097$ 4.1% *vs*. 4%, $P = 0.81$ 6.1 days *vs*. 5.9 days, $P = 0.019$ in median 3% *vs*. 2.8%, $P = 0.877$ 4.1% *vs*. 4.6%, $P = 0.258$
Cao *et al*.[32]	Comparison of short and long term outcomes after a lobectomy RATS and VATS n = 941 patients For meta-analysis for short-term outcomes n = 160 RATS and n = 372 Open	RATS *vs*. Open Complication rate Length of hospital stay	RR 0.77 (95%CI 0.54-1.09) $P = 0.14$ Shorter in RATS group $P < 0.05$

Paul *et al*.[33]	Comparison of short-term outcomes after a lobectomy RATS and VATS in a sample of a nationwide database n = 2498 RATS n = 37,595 VATS	RATS *vs*. VATS Length of hospital stay Complication rate In-Hospital mortality Total Costs	5 days *vs*. 5 days, P = 0.23 in median 50.1% *vs*. 45.2%, P = 0.32 0.7% *vs*. 1.3%, P = 0.15 22.582$ *vs*. 17.874$ P < 0.001 (Median)
Emmert *et al*.[35]	Comparison of short-term outcomes after a lobectomy RATS and VATS n = 3758 RATS n = 58,677 VATS	RATS *vs*. VATS Length of hospital stay Operative time Chest tube duration Mortality	-1.08 days (95%CI -2.33 to -0.17) P = 0.078 mean difference 8.97 min (95%CI -28.12 to -46.07) P = 0.56 mean difference -0.71 days (95%CI -1.5 to -0.1) P = 0.064 mean difference OR 0.52 (95%CI 0.29-0.93)
Louie *et al*.[34]	Comparison of short term outcomes after a lobectomy RATS and VATS n = 1220 RATS n = 12,378 VATS National Database	RATS *vs*. VATS Operative time Air Leak > 5 days Length of hospital stay < 4 days 30-day mortality	186 min *vs*. 173 min P < 0.001 10% *vs*. 9.8% P = 0.8135 48% *vs*. 39% P < 0.001 0.6% *vs*. 0.8% P = 0.4
Wei *et al*.[36]	Comparison of short-term outcomes after a lobectomy RATS and VATS n = 4727 RATS n = 56,232 VATS before matched analysis	RATS *vs*. VATS for matched cohort 30-day mortality Postoperative morbidity	RR 0.12 (95%CI 0.01-1.07) P = 0.06 RR 0.95 (95%CI 0.83-1.08) P = 0.41

DFS: disease free survival; HR: hazard ratio; OS: overall survival; OR: odds ratio; RATS: robotic-assisted thoracic surgery; RR: risk ratio; VATS: video-assisted thoracic surgery; WMD: weighted mean difference; NSCLC: non-small cell lung cancer

principles as anatomical dissection and allows better lymph node dissection[20,21]. The main limitations for the wide deployment of RATS are the higher cost of the procedure compared to VATS[22] and logistical issues.

Lymph node dissection and nodal upstaging by RATS, VATS, and open thoracotomy

Intraoperative lymph node assessment is a critical component in the surgical treatment of NSCLC. Since the development of VATS, there has been controversy concerning lymph node dissection performed by VATS compared to open surgery. Studies have described the feasibility of using VATS to perform complete lymph node dissection and even nodal upstaging, although less commonly than by open surgery. With its intrinsic features, lymph node dissection has been described as easier to perform by RATS than by VATS[21,23].

Kneuertz *et al*.[24] recently published a propensity-score adjusted comparison of lymph node upstaging by RATS, VATS, and open surgery during lobectomy for a cN0/N1 NSCLC in two centers. Between 2011 and 2018, 911 patients were included (254 RATS, 296 VATS, and 261 open surgery). The overall rate of lymph node upstaging was highest with open lobectomy (21.8%), followed by RATS (16.2%) and VATS (12.3%) (P = 0.03), with no difference concerning mediastinal N2 upstaging (P = 0.6). More nodes were sampled by open surgery (4) than by RATS (3.8) and VATS (3.6) (P = 0.001). Finally, on multivariate analysis, the rate of lymph node upstaging was lower for VATS compared to open surgery (OR 0.5, 95%CI 0.29-0.85, P = 0.01) and not different between RATS and open surgery (OR 0.72, 95%CI 0.44-1.18, P = 0.19). Multiple contemporary studies have reported the same overall long-term survival between VATS lobectomy and open lobectomy, which suggests that there is no decreased long-term survival for patients treated by VATS[25,26]. Medbery *et al*.[27] reported a lower rate of nodal upstaging with VATS than with open surgery (P < 0.001), but, in the subgroup of patients operated on in a university hospital, there was no difference between groups (P = 0.08). Recently, Yang *et al*.[28] reported an absence of difference in the rate of nodal upstaging of patients with clinical T1-T2 N1 M0 NSCLC and performed by VATS or open surgery (12% and 10.5%, respectively, P = 0.41). The five-year overall survival was not different between the two groups (48.6% and 48.7%, respectively, P = 0.76). With RATS, the rate of nodal upstaging was not different compared to open surgery, and higher than with VATS[20,21].

Main results of meta-analysis and systematic reviews according to lobectomy performed by RATS, VATS, or open surgery

Ng *et al.*[13] published the latest and most extensive systematic review and meta-analysis in 2019 comparing VATS to open thoracotomy, VATS to RATS, and also multiport and uniport VATS. They included 138 studies and 7 randomized controlled trials with 369,793 patients. They analyzed short-term outcomes such as complications, mortality, and oncologic quality criteria with lymph node dissection and long-term outcomes. They also analyzed functional data with pain, quality of life, pulmonary function, and cost-effectiveness. They reported a lower complication rate with VATS lobectomy than with open lobectomy (OR 0.64, 95%CI 0.59-0.71, $P < 0.001$), and no difference in mortality rate (OR 0.78, 95%CI 0.56-1.07, $P = 0.12$). The rate of nodal upstaging was lower with VATS than with open surgery (OR 0.71, 95%CI 0.58-0.87), with no difference in the number of lymph nodes resected ($P = 0.18$) or nodal stations explored ($P = 0.49$). They found no difference in the rate of nodal upstaging between VATS and RATS (OR 1.02, 95%CI 0.85-1.22, $P = 0.87$). Length of hospital stay was shorter after VATS than open surgery, –1.9 days (95%CI –2.25 to 1.54, $P < 0.001$), but there was no difference between VATS and RATS, –0.16 days (95%CI 0.81-0.48, $P = 0.62$). Concerning long-term outcomes, five-year overall survival was improved after VATS lobectomy compared to open lobectomy (OR 1.35, 95%CI 1.17-1.56, $P < 0.0001$), with no difference observed in disease free survival (OR 1.15, 95%CI 0.94-1.40, $P = 0.18$). There was no difference in five-year overall survival between VATS and RATS (OR 0.79, 95%CI 0.47-1.33, $P = 0.38$) or in five-year disease free survival (OR 0.71, 95%CI 0.44-1.14, $P = 0.16$). The main results of the reports analyzed in this article are presented in Table 1.

O'Sullivan *et al.*[14] published in 2018 the first systematic review and meta-analysis and concluded that RATS lobectomy significantly improved the short-term outcomes of patients more than VATS or open lobectomy. After RATS lobectomy, compared to open lobectomy, there was an improvement in short-term outcomes, with fewer complications (OR 0.67, 95%CI 0.58-0.76, $P < 0.00001$), lower 30-day mortality (OR 0.53, 95%CI 0.33-0.85, $P = 0.08$), and shorter length of hospital stay with weighted mean difference (WMD) of –1.4 days (95%CI –1.96 to 0.85, $P < 0.00001$), but longer operative times with WMD of 65.56 min (95%CI 53.66-77.46, $P < 0.00001$). After RATS lobectomy, compared to VATS lobectomy, there was a lower rate of 30-day mortality (OR 0.61, 95%CI 0.45-0.83, $P = 0.001$), with longer operative times with WMD of 4.98 min (95%CI 2.61-7.36, $P < 0.001$).

Adams *et al.*[29] in 2014 published one of the first retrospective multicenter comparisons of short-term outcomes after lobectomy performed by RATS, VATS, or open surgery and concluded that RATS was equivalent to VATS for all intraoperative and postoperative outcomes, but allowed better short-term outcomes compared to open surgery. Their main results were lower rates of postoperative blood transfusion (0.9% *vs.* 7.8%, $P = 0.002$), fewer air leaks of more than five days (5.2% *vs.* 10.8%, $P = 0.05$), shorter duration of chest tube placement (3.2 days *vs.* 4.8 days, $P =< 0.001$), and shorter length of stay (4.7 days *vs.* 7.3 days, $P < 0.001$). Agzarian *et al.*[30], Kent *et al.*[15], and Rajaram *et al.*[31] concluded that RATS was not superior to VATS for perioperative outcomes. Compared to open surgery, RATS was found superior with fewer perioperative outcomes[32].

Until the publication of O'Sullivan *et al.*[14], systematic reviews and meta-analyses[32-36] found small significant differences in short-term outcomes between RATS and VATS lobectomy or no difference between these two minimally invasive surgical approaches.

Minimally invasive approaches for locally advanced NSCLC

Petersen *et al.*[37] in 2006 were among the first to demonstrate that VATS lobectomy was safe and feasible for selected patients with NSCLC who had received induction chemotherapy or chemoradiotherapy. They reported short-term outcomes with no increase in the number of adverse events after VATS resection and with the same oncologic efficacy. Yang *et al.*[38] reported a propensity score matched analysis, in which survival of patients operated by VATS after induction chemotherapy with or without radiotherapy was

similar to those who were operated by an open approach (P = 0.56). Moreover, 30-day mortality was similar (P = 0.69). Veronesi et al.[39] reported a multicenter retrospective cohort of patients with stage III NSCLC and operated by a RATS procedure in seven high volume centers. They reported 223 NSCLC, 32% of which were diagnosed cN2 preoperatively and 68% intraoperatively. The rate of conversion to thoracotomy was 9.9%, and the rate of Grade 3 and more complications was 10.3%. For patients who received neoadjuvant chemotherapy, the rate of conversion to thoracotomy was 15%, the rate of Grade 3 and 4 complications was 12%, and all were resected with R0 margins. Overall 90-day mortality was 4% but no patient who received neoadjuvant chemotherapy died. Three-year overall survival was 61.2%, while 60.3% in the group of patients treated by neoadjuvant chemotherapy (P = 0.6).

DISCUSSION

In this mini-review, we compare short-term outcomes between lobectomy performed by minimally invasive VATS and RATS and lobectomy by open surgery. For several decades, VATS lobectomy has allowed better short-term outcomes compared to open surgery with at least the same long-term oncologic outcomes. These results were obtained by systematic review and meta-analysis of retrospective series and of some randomized controlled trials.

Before discussing the reported results, the common points and differences among RATS, VATS, and open approaches are clarified. Together, there are three surgical approaches but two surgical feelings and two resection concepts for lung lobectomy.

Regarding surgical feelings, also called haptic - force and tactile - feedback, compared to open surgery, VATS allows us to feel each tension exerted on the tissues, because we directly manipulate the tissue, lung, lymph nodes, and other structures. Conversely, the robotic platform is a robotic device guided by the surgeon using a digital interface. With the Da Vinci platform, we do not receive sensitive feedback in our hands. This lack of feedback is one of the criticisms made of this surgical tool. However, "when one feeling is lacking, we say that another develops". Thus, surgeons who can no longer rely on touch see their eyes sharpen, becoming an extension of their hands. With training, they learn and feel the tension exerted on the tissue by seeing the latter exerted on the tissue, allowing them to exceed this limit. The surgeon assistants who expose and retract the lung will also help the operator surgeons, because they can feel the exerted tension on lung by the robot and thus the operator. Nevertheless, robotic surgery industries are studying haptic feedback, but each robotic system is different, thus each research system is different. Moreover, it is important to first understand how we perceive force and tactile information, because it will affect the way we design haptic displays[40].

Regarding resection concepts, compared to VATS and the anterior approach - e.g., fissureless technique - RATS allows us to mimic open surgery techniques. The robotic platform allows thoracic surgeons to perform a lobectomy, as they would have done using an open approach. Conversely, the fissureless approach in VATS lobectomy is a necessary adaptation of a surgical technique.

In 2016, Bendixen et al.[18] published a randomized controlled trial comparing lobectomy by VATS and by anterior muscle sparing thoracotomy. For VATS, the authors observed less pain on Postoperative Day 1 (P = 0.0012) and during the year after resection (P < 0.0001), as well as better quality of life according to EuroQol 5 Dimensions (EQ5D) (P = 0.014). Nevertheless, they found no difference between VATS and thoracotomy for postoperative Grade 3 and 4 adverse events, and quality of life according to the European Organisation for Research and Treatment of Cancer 30-item quality of life questionnaire (QLC-C30) (P = 0.13). More recently, the first results of the randomized controlled VIOLET study[41] confirmed better short-term outcomes after lobectomy by VATS than by open surgery.

Postoperative complications affect mortality, and major one, as Grades ≥ 3 according to the Clavien-Dindo classification, have a significant impact on mortality but are rare, with a rate of 4.3% in the multicenter and retrospective review published by Cao *et al*.[42]. This rate was comparable to outcomes of the CALGB 39802 study, which reported a rate of 7.4% for Grade ≥ 3 postoperative complications after a VATS lobectomy[43]. In robotic practice, better short-term outcomes were observed after lobectomy by RATS than by open thoracotomy. However, most meta-analyses reported the same short-term outcomes, with as negative points longer operative times and more costly procedures compared to VATS lobectomy[13,15,29-31,34-36,44]. Only O'Sullivan *et al*.[14] reported better short-term outcomes with fewer adverse events after lobectomy by RATS compared to VATS in a systematic review with meta-analysis. Nevertheless, some authors reported in retrospective studies a clear benefit of RATS compared to VATS. Reddy *et al*.[45] recently reported a propensity-matched comparison of lobectomies by surgeons who performed 20 or more VATS or RATS procedures annually. With 838 patients in each group, they observed in the RATS group a lower rate of conversion (4.8% *vs*. 8%, $P = 0.007$), a lower rate of 30-day complications (33.4% *vs*. 39.2%, $P = 0.0128$), and no difference in mortality rate, but with longer operative times by 25 min ($P < 0.0001$). They concluded in favor of RATS lobectomy for surgeons performing more than 20 procedures annually. One complication that is less often reported after robotic lobectomy is postoperative anemia requiring blood transfusion. Indeed, robotic surgery allows performing very precise gestures and in particular elective hemostasis during hilar dissection and lymph node resection. For example, Adams *et al*.[29] reported fewer blood transfusion after a RATS lobectomy compared to a VATS or open lobectomy ($P < 0.05$).

Cost is presented as one of the major drawbacks of RATS[22]. In the current context of resource management, Gondé *et al*.[46] conducted a precise assessment of the economic impact of RATS surgical innovation compared to VATS. RATS lobectomy was found more expensive than VATS lobectomy, and median total costs were €10,972 *vs*. €9637 ($P = 0.007$). Costs related to length of stay were not different ($P = 0.061$), but excessive costs reported in the RATS group were explained by expensive medical devices and supplies used for RATS lung resection ($P = 0.004$). Nevertheless, these authors reported a significantly lower cost of their minimally invasive techniques compared to the mean cost in France ($P = 0.001$). Conversely, VATS was found to be a cost-effective alternative compared to thoracotomy in the randomized controlled trial of Bendixen *et al*.[47], with a savings of €4267 ($P < 0.001$). Subramanian *et al*.[48] reported that, compared to open lobectomy, RATS lobectomy was 13% more expensive ($P < 0.001$) and VATS lobectomy 2% less expensive ($P = 0.007$). In their report, they analyzed operating room costs and in-hospital costs from patients operated between 2008 and 2014 in Florida, with data from the Healthcare Cost and Utilization Project Florida State Inpatient Database. Minimal approaches were also associated with improved clinical outcomes compared to open lobectomy ($P = 0.016$), and increased operating room costs were compensated by in-hospital savings. Recently, Kneuertz *et al*.[49] reported a cost analysis performed at their center. They analyzed data from 697 patients operated by RATS (n = 296), VATS (n = 161), and open (n = 240) for a lobectomy between 2012 and 2017 and performed a propensity score adjustment. Unlike our report[46], and that of Subramanian *et al*.[48], the overall cost - including operating room costs and in-hospital costs - of the three approaches were similar: RATS $17,223, VATS $17,260, and open $18,075 ($P = 0.48$). Nevertheless, RATS and VATS approaches were associated with higher operating room costs - RATS $9912 and VATS $9491 - compared to open thoracotomy - $8698 ($P = 0.001$). Finally, according to their experience, despite the higher operating room costs calculated for RATS and VATS, it was recovered by postoperative costs reductions associated with improved postoperative outcomes and shorter hospital stay ($P < 0.001$). These three articles[46,48,49] reported higher operating room costs for RATS lobectomy but compensated by improved outcomes compared to thoracotomy. Nevertheless, RATS will always be more expensive, and our goal is to reduce this economic gap. Because patients are well prepared and conditioned within the framework of enhanced recovery protocols, they allow better short-term outcomes for patients operated by thoracotomy and lead to fewer adverse events, shorter length of hospital stay, and logically cost reductions for these patients in 2020 compared to patients operated 5 or 10 years ago.

Minimally invasive lobectomy performed by VATS or RATS is recommended for early stage NSCLC[1] and the majority of series in this mini-review included stage I NSCLC. Some authors advocate the effectiveness of VATS and RATS for loco-regionally advanced NSCLC. More and more studies have described the effectiveness of a VATS approach for N positive status[50] and combined resection of a lobe, e.g., with the chest wall[51], the superior vena cava[52] or a sleeve resection[53]. For stage IIIA NSCLC, a VATS approach allowed at least the same long-term outcomes compared to thoracotomy, but with better short-term outcomes[38]. Extended indications for loco-regionally advanced NSCLC are being explored in robotic thoracic surgery. With the benefits of improved visualization, stability, dexterity, and accuracy, some technical aspects of lobectomy, with complete lymph node dissection, are described as easier to perform by RATS than by VATS[23,54-56], with no difference in long-term outcomes.

Performing minimally invasive surgery using a digital interface has enabled the use of innovative techniques and concepts. The first concept is the use of the simulation tool in the technical learning process. Thus, before performing their first minimally invasive lung resection on a patient, trainee surgeons are able to train on high definition digital simulators close to the reality of the operating room and thus improve their technical skills[57,58]. Moreover, with a high-definition CT scanner and 3D modeling, it is possible to precisely plan a complex lung resection such as a segmentectomy on 3D representation[59]. In addition, 3D modeling can be visualized on screen. This augmented reality can be used for liver surgery, for example, but still requires development for lung resection. 3D augmented reality could be used for VATS and RATS surgery and even for open surgery, by using specific glasses. The second concept is the use of safety controls via the robotic platform. Thus, before starting a procedure, security elements are specified to unlock the robot or even the optics of the VATS column to prevent intraoperative accidents.

The majority of the included studies did not use propensity matching, but included heterogeneous groups of patients in terms of disease stage, comorbidity, and surgical approaches. This heterogeneity could potentially mask some results, but reflects "real-life practices in our unit". As such, this mini-review does not provide conclusive evidence regarding the superiority of RATS compared to VATS for short-term outcomes. A randomized controlled trial is required to provide conclusive answers.

CONCLUSION

Robotic lobectomy could be a valid alternative to open surgery, and provides at least the same short-term outcomes compared to VATS. Based on the findings of recent meta-analyses, lobectomy performed by RATS compared to VATS could allow lower 30-day morbidity and mortality, but with longer operative times and higher surgical costs. According to recent reports, robotic technology seems to be a reasonable alternative to VATS and open surgery. This result must be interpreted with caution, as we cannot exclude an inherent bias related to meta-analyses. A randomized controlled trial with cost analysis and long-term follow-up may be useful to understand the role of robotic technology in thoracic surgery for the benefit of patients with NSCLC.

DECLARATIONS

Authors' contribution
Collected and selected articles: Montagne F, Baste JM
Participated in manuscript, writing and review: Montagne F, Baste JM
Participated in reviewing: Bottet B, Sarsam M, Mbadinga F, Chaari Z, Rinieri P, Melki J, Peillon C

Availability of data and materials

Not applicable.

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Conflicts of interest

Baste JM is proctor for Intuitive Surgical® Medtronic® and Baxter®.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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