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Robotic Surgery for the Thoracic and Vascular Surgeon

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Abstract

In the last two decades, robotic-assisted approaches have gained popularity as alternatives to conventional open and minimal-invasive surgery (MIS). The robotic approach combines the concepts of the traditional MIS with the latest technological advancements, enabling the surgeon to control the instrumentation using a robotic device connected to a remote console. With this approach, the surgeon obviates the known drawbacks of conventional MIS, such as the reduced in-depth perception and hand-eye coordination. Since its introduction, numerous robotic-assisted procedures have been developed and tested across nearly all surgical fields. Data from previous studies have shown that a great majority of these techniques are feasible and have favourable treatment outcomes. In the field of thoracic and vascular surgery, two disciplines often combined in Belgium, robotic approaches have been implemented in the treatment of a wide array of disorders including lung cancer, mediastinal tumours, thoracic outlet syndrome, diaphragmatic paralysis, sympathectomy, aortobifemoral bypass surgery and division of the arcuate ligament for median arcuate ligament syndrome (MALS). Despite this increasing popularity, there are still a number of controversies regarding robotic surgery. There are only limited data on the cost-effectiveness of robotic surgery and its objective proven benefit over conventional MIS. In this review, we summarise the latest data on robotic approaches for the most relevant thoracic and vascular disorders.

Keywords: Robotic surgery, Minimal-invasive surgery, Thoracic surgery, Vascular surgery, RATS, VATS, RAAS

1. Introduction

The advent of minimally invasive surgery (MIS) has clearly changed the landscape for surgical practice worldwide. By combining multiple technological developments such as high-definition cameras and surgical microinstruments, surgeons are able to perform more and more complex procedures through small incisions [1]. Since the introduction of MIS, safe and feasible laparoscopic and thoracoscopic surgical procedures have been developed for a large variety of operations. For the majority of these procedures, studies have shown that the minimal-invasive approach results in fewer complications, reduced hospital stays, and faster return to normal functions compared to their respective open approach [2, 3]. However, despite these clear advantages of MIS, there are a number of drawbacks as well. Proficiency in MIS requires intensive, continuous training and often involves steep

learning curves for surgeons in training. Despite their training, the surgeons are often confronted with a number of drawbacks such as poor depth perception, reduced spatial coordination due to the two-dimensional optics, a lack of instrument flexibility, reduced force feedback while manipulating tissues, and counter-intuitive movements [4, 5]. In addition, surgeons are often exposed to physical strains from standing in non-comfortable positions for extended periods of time. These difficulties can significantly amplify the complexity of surgical procedures and their outcome.

In more recent years, robotic-assisted surgery has emerged as a new minimal-invasive approach to surgery, integrating current technological advancements in 'traditional' MIS. The concept of robotic-assisted surgery is to enable the surgeon to control the laparoscopic/thoracoscopic instrumentation through a robotic device that is connected to a remote console. Using this technology allows for three-dimensional optics, enhanced range of intuitive instrument motions (even more than the normal open situation), and improved ergonomics [3, 6]. This type of robotic-assisted surgery first gained prominence in the field of urology, mainly for performing radical prostatectomy and complex bladder operations [7]. Since its introduction, the applications for surgical robots has expanded into almost all surgical fields, resulting in its current wide-scale use. For thoracic and vascular surgeons, a growing number of studies have shown that robotic-assisted surgery is feasible and results in favourable outcomes as well [4, 8]. These benefits have mainly been shown in the field of mediastinal tumours and lung cancer surgery, however, the efficacy of robotic-assisted surgery has also been proven for other thoracic and vascular procedures such as first-rib resection, sympathectomy, diaphragmatic paralysis, median arcuate ligament release, and aorto/ilio-femoral bypass surgery for occlusive disease [4, 9].

Despite these advantages and the increasing popularity of these robotic-assisted approaches, there are still controversies regarding the implementation and the use of these approaches, such as the generally high operating costs, lack of haptic feedback, the size of the system, and longer total operative times due to installation of the robotic system [7, 10]. Furthermore, there is a lack of definite data from large prospective studies comparing short-term and long-term outcomes of open surgery with 'traditional' MIS and robotic-assisted surgery in all aspects, including the ergonomics for the surgeon. Nevertheless, these studies are necessary to truly demonstrate the effectiveness and superior outcomes of these emerging surgical approaches. In this chapter review, we summarise the latest data on surgical techniques and treatment outcomes for robotic-assisted thoracic and vascular surgery.

2. Robotic-assisted thoracic surgery

In the field of thoracic surgery, video-assisted thoracoscopic surgery (VATS) remains the gold standard approach for thoracic surgery, and it is performed for almost all thoracic surgical indications [4]. In the last few years, robotic-assisted thoracoscopic surgery (RATS) has gained popularity as alternative to VATS due to the flexibility of its endo-wrist instruments, the three-dimensional visualisation, and the more precise and intuitive movements [1, 11]. The majority of studies comparing RATS to VATS and/or thoracotomy have been performed in the field of thoracic oncology, in which the benefits of RATS have already largely been established [12]. However, there is an increasing amount of studies that show similar benefits of RATS in other (non-oncological) thoracic surgical procedures [13]. In this section, we will highlight and review the most commonly performed oncological and non-oncological RATS procedures.

2.1 Lung cancer surgery

Lung cancer is worldwide the most common malignancy and one of the leading causes of cancer-related deaths [14]. Despite the widespread implementation of measures mitigating tobacco use, an overall increase in new cases of non-small cell lung cancer (NSCLC) has been noted, mainly due to rising incidence rates in developing countries [15]. The majority of these new lung cancer cases are diagnosed during advanced stages, resulting in low overall five-year survival rates [14]. In these advanced stages, treatment modalities are limited and have minimal effects on overall and disease-free survival. However, due to advancements in diagnostic techniques and imaging modalities, an increasing number of NSCLCs are being detected at earlier stages of disease [16]. In the near future, the number of newly-diagnosed early stage lung cancers will likely increase due to the implementation of lung cancer screening programmes. The NELSON-trial and the NLST-trial have both shown that screening patients with high-risks of developing lung cancer with low-dose chest computed tomography (CT) scans results in significantly lower mortality rates due to earlier cancer detection [17, 18].

For early-stage NSCLC, the gold standard remains surgical management by means of lobectomy with hilar and mediastinal lymph node dissection [19, 20]. Currently, VATS lobectomy is the technique of choice for this procedure as several large-scale studies have shown that VATS results in fewer perioperative complications, less pain, and faster recovery times compared to the traditional open approach [21, 22]. However, in the last decade, RATS has been gaining popularity as a minimal invasive approach due to its ability to overcome the previously described drawbacks of conventional VATS [12]. Despite a lack of well-powered randomised controlled trials comparing RATS to VATS or open surgery for the treatment of (early stage) lung cancer, a growing body of literature has demonstrated a clear advantage of lobectomy by RATS over thoracotomy regarding perioperative blood loss, postoperative analgesia need, postoperative recovery, hospital length of stay (LOS), and 30-day mortality rates [13]. In contrast, results from studies comparing RATS to VATS are less conclusive and, often, contradictory. In a recent meta-analysis of 3239 patients comparing RATS to VATS, a lower 30-day mortality and conversion rate to open surgery was seen in favour of RATS [23]. Similar studies have also shown improved survival rates, fewer postoperative complications, and shorter hospital stays for RATS compared to VATS [24]. However, in a propensity-matched analysis by Oh et al., no difference in mortality was detected between VATS and RATS [25]. Similarly, no significant difference in survival was found in the database analysis of the Society of Thoracic Surgeons (STS) which included 1220 RATS and 12378 VATS lobectomies [26].

Regarding oncological outcomes, only a limited number of studies have been performed comparing RATS to open surgery and/or VATS. There is evidence suggesting that RATS results in increased rates of nodal upstaging and yields higher numbers of nodal stations sampled. However, in a recent data analysis by Hennon et al., 64,676 patients with NSCLC from the National Cancer Database (NCDB) in the USA were analysed for lymph node yield and nodal upstaging. The results of their study did not show any significant difference between the three approaches. The authors concluded that both RATS and VATS are non-inferior to open thoracotomy for intraoperative lymph node evaluation [27]. In addition to the possible benefits regarding treatment and oncological outcomes for lobectomies, an increasing number of experts are advocating for the use of RATS in sublobar resections. For elderly patients, patients with comorbidities, or patients with limited pulmonary reserve, sublobar resections such as wedge resections and segmentectomies have been proposed as viable alternatives [11, 28]. Despite efforts to compare the oncological

and survival outcomes of sublobar resections to lobectomy, there is still no clear consensus on whether sublobar resections are indeed non-inferior to lobectomy. Some authors suggest that sublobar resections result in lower overall survival rates, higher positive resection margins, higher recurrence rates, and inadequate lymph node sampling [29]. However, there is a growing number of studies suggesting that segmentectomy has similar overall and disease-free survival rates as lobectomy [30]. Furthermore, sublobar resections have also been associated with improved postoperative quality of life (QoL) [16]. For robotic segmentectomy, the current data suggests that treatment outcomes and complication rates are similar to VATS. In a recent retrospective study by Xie et al., 215 patients that underwent atypical or anatomical segmentectomy by RATS or VATS were analysed for short-term treatment outcomes. The authors concluded that RATS was a safe approach and even resulted in higher lymph node sampling rates and fewer postoperative complications compared to VATS [31].

Even for treating centrally located NSCLC lesions, emerging evidence is suggesting that RATS may play a major role in the near future. A recent retrospective study by Qiu et al. compared treatment and oncological outcomes of RATS to VATS and open surgery in 188 patients undergoing sleeve lobectomy for centrally located NSCLC. RATS was non-inferior to both VATS and open surgery regarding oncological prognosis. However, the robotic group had significantly less blood loss, shorter operative times, and reduced tube drainage times compared to the two other groups. The authors concluded that robotic sleeve lobectomy is a safe, feasible and effective procedure for centrally located NSCLC [32]. Despite all these promising studies, these findings have not been demonstrated in large prospective series or randomised controlled trials (RCT).

2.2 Mediastinal masses

Mediastinal masses in the anterior, middle or posterior compartment are a heterogeneous group that account for approximately 3% of all thoracic lesions. The most common mediastinal masses are thymomas, bronchogenic cysts, neurogenic tumours, and thyroid masses. These lesions derive from different germ layers located in various parts of the thoracic cavity [33]. In the past, surgical removal of these mediastinal masses was generally performed using a median sternotomy, posterolateral thoracotomy, or hemi-clamshell sternotomy, often resulting in significant postoperative morbidity [34]. However, the increasingly widespread use of minimal-invasive approaches in other surgical domains has resulted in a similar shift in treatment approaches for mediastinal tumours [35]. Thoracoscopic thymectomy was first described in 1993 and VATS has since become one of the standard approaches for thymic and non-thymic malignancies [35]. Earlier studies have shown that VATS is associated with less perioperative blood loss, shorter operation times, and less chest tube drainage compared to open procedures [36]. In the past two decades, robotic surgery has gained popularity in the treatment of mediastinal masses as well. Similar to the situation for lung cancer surgery, RATS has advantages over conventional VATS due to its three-dimensional image and multi-articulated instruments, providing easy access to the small mediastinal space and allowing safe removal of mediastinal masses [37, 38]. While comparisons of treatment outcomes and postoperative complications between open and MIS approaches have been performed before, few studies have directly compared VATS to RATS for mediastinal masses.

In a retrospective study by Qian et al., 123 patients with early-stage thymoma were analysed to compare treatment outcomes for VATS, RATS, and median sternotomy. The authors concluded that RATS and VATS are both feasible techniques

for early-stage thymomas with similar oncological outcomes compared to open surgery. However, their data did show more favourable outcomes for RATS regarding post-operative pleural drainage duration time, drainage volumes, and hospital LOS [39]. Other recent studies have corroborated these findings as well. Zeng et al. retrospectively analysed 274 patients that underwent multiportal VATS, uniportal VATS, or RATS resection of a mediastinal mass. Compared with multiportal VATS, uniportal VATS and RATS had a significantly shorter chest tube placement time and hospital LOS without increasing the incidence rate of complications. The RATS approach was associated with better intraoperative safety and was considered non-inferior regarding postoperative outcomes compared to multiportal VATS [40]. In a very recent retrospective cohort study using the National Inpatient Sample (NIS) database, an estimated total of 23,087 patients that underwent thymectomy were included to compare outcomes after open, VATS, and RATS thymectomy. The majority of patients were treated for thymoma or myasthenia gravis, with approximately 16,025 patients (69%) in the open surgery group, 4,119 (18%) in the VATS group, and 3,097 (13%) in the RATS group. In the analysed period of 2008–2014, trend analysis revealed a decline in open surgery, while the performance of VATS and RATS had increased. No significant differences in overall complication rates or hospital LOS were found in this study. However, RATS was associated with lower rates of cardiac complications and haemorrhage [41]. Even for the rarer posterior mediastinal tumours, recent data suggests that RATS may be superior in terms of postoperative blood loss and hospital LOS compared to VATS [4].

2.3 First rib resection

Thoracic outlet syndrome (TOS) is a complex disorder that comprises a myriad of possible symptoms which arise from compression of the brachial plexus, subclavian artery, and/or the subclavian vein. This compression generally occurs in the triangular space referred to as the thoracic outlet, which is located between the first rib, the clavicle, and the scalene muscles [42]. The majority of patients with TOS can be treated with non-surgical measures such as medication, posture correction, physical therapy, or taping. However, in a relatively small number of patients, these conservative treatments fail to alleviate the symptoms, often resulting in significant morbidity [43]. In these patients, or when vascular structures are involved, surgical decompression with removal of the first rib is usually necessary. Over the last decades, several types of surgical approaches and techniques have been described. Historically, extrathoracic approaches have used a supraclavicular or transaxillary incision to resect the first rib. Despite their well-documented effectiveness, many authors have asserted that these approaches are regularly associated with complications such as brachial plexus injury or vascular injury [44].

The intrathoracic approach using VATS has been the most popular approach in the last decade, owing to the theoretical advantage of fewer postoperative neurovascular complications and incomplete resections [45]. In recent years, the robotic-assisted approach has rapidly gained ground as a viable alternative to VATS due to its superior optics and instrument control [44]. However, this remains a relatively new field with only a limited number of studies published reporting outcomes of RATS first rib resections. Data from retrospective studies and case series from the last decade suggests that the robotic approach is safe, effective, and non-inferior to the VATS approach [46]. In a recent single-center, prospective study by Burt et al. RATS first rib resection was compared to the conventional supraclavicular approach in 116 patients (66 RATS and 50 open surgery). Postoperative pain and analgesia need was significantly lower in the robotic approach group. Furthermore, RATS was associated with fewer cases of brachial plexus palsy and overall complication

rates [47]. Despite these promising results, there is still a lack of data from larger, prospective studies comparing RATS, VATS, and open approaches for first rib resections.

2.4 Sympathectomy

Presently, hyperhidrosis is the main indication for sympathectomy, which can be performed through various surgical approaches, such as the posterior thoracic approach, transaxillary approach, transthoracic approach, VATS approach, and RATS approach. The sympathectomy itself is usually performed by ganglionectomy, clipping, or ablation of the dorsal sympathetic chain [48]. The extent to which the sympathectomy is performed is a controversial subject as it is correlated to the incidence of complications. More extended sympathectomy has been associated with higher rates of compensatory hyperhidrosis. Despite a lack of clear guidelines, the general consensus is to perform an interruption of T3 and T4 for palmar hyperhidrosis, and interruption of T4 and T5 palmar and axillary or palmar, axillary, and pedal hyperhidrosis [49].

A more precise variation of this technique is the selective postganglionic sympathectomy, which involves an interruption of only the postganglionic rami, leaving the sympathetic trunk and ganglia intact. The branches accompanying intercostal nerves 2–4 to the upper extremities are interrupted selectively [50]. Previous studies have shown that this technique of selective postganglionic sympathectomy has success rates up to 95% with only minimal rates of compensatory hyperhidrosis [51]. Only limited data is available regarding robotic selective sympathectomy. However, data from single-institution case series have shown that robotic-assisted selective (postganglionic) sympathectomy is a safe technique with favourable results [52, 53]. In a recent prospective case series by Gharagozloo et al., a total of 47 patients underwent two-staged bilateral robotic selective dorsal preganglionic and postganglionic sympathectomy. Their data showed excellent relief of hyperhidrosis, and minimal rates of compensatory hyperhidrosis and complications. The authors used a two-staged approach to allow the transient compensatory hyperhidrosis to dissipate and to obviate postoperative thoracic pain due to the use of robotic ports [48]. Despite a lack of larger prospective and randomised trials, the current evidence suggests that the robotic-assisted approach has the potential of accomplishing hyperselective sympathectomy with accuracy and minimal rates of compensatory hyperhidrosis and complications such as Horner's syndrome.

2.5 Diaphragmatic plication

Diaphragmatic paralysis is an uncommon condition that is characterised by elevation of a hemidiaphragm. If symptomatic, patients often experience dyspnoea during exercise, orthopnoea, fatigue, insomnia, and an overall reduced quality of life. In adult patients, the most common causes of diaphragmatic paralysis are idiopathic, tumour invasion of the phrenic nerve, or damage to the phrenic nerve during cardiothoracic surgery [54]. Surgical treatment is indicated exclusively for symptomatic patients, and the preferred surgical technique is (hemi)diaphragmatic plication [55]. The traditional method is the open transthoracic plication, and is still widely used today. However, an increasing number of surgeons are moving towards less invasive approaches such as laparoscopy or thoracoscopy. VATS diaphragm plication has already demonstrated to be a safe and feasible technique for symptomatic patients [56, 57]. However, technical difficulties due to the limited workspace in the thorax and the elevated hemidiaphragm often lead to the adoption of a (mini)thoracotomy. Robotic-assisted surgery offers all the benefits of MIS while

simultaneously providing the surgeon the same dexterity as the open approach. Several case studies and small case-series have reported excellent outcomes with the robotic approach for diaphragmatic plication [58, 59]. However, robust and conclusive data regarding long-term outcomes are still missing.

3. Robotic-assisted vascular surgery

In the last few decades, the field of vascular surgery has changed dramatically with the introduction of endovascular surgery. There has been a significant paradigm shift towards these endovascular approaches for the treatment of a wide array of venous and arterial diseases [8]. However, despite the fact that many vascular surgeons have been willing to embrace innovative, minimally-invasive techniques, the implementation of laparoscopic vascular surgery has only been a relatively minor success. This has mainly been due to the difficulties associated with laparoscopic vascular surgery such as the suturing of vascular anastomoses and long clamping times [9]. Furthermore, for an increasingly large number of procedures, an endovascular technique has been developed. However, with the advent of robotic-assisted approaches, new opportunities have risen for vascular surgeons, especially for disease states that are not amenable to endovascular interventions and for which current approaches are technically challenging or associated with significant morbidity. In this section, we will discuss the latest data regarding indications and outcomes of robotic-assisted vascular surgery.

3.1 Median arcuate ligament release

Median arcuate ligament syndrome (MALS) is caused by compression of the celiac artery and plexus by the median arcuate ligament of the diaphragmatic crura [60]. In a normal population, the median arcuate ligament crosses the aorta anteriorly above the celiac origin between levels T11 and L1. However, in approximately 12–49% of the population, an anatomic variant exists in which the ligament passes inferiorly, causing compression of the celiac artery and ganglion. The majority of patients with this anatomical variant are asymptomatic due to a rich network of collateral vessels between the celiac and superior mesenteric arteries. However, a number of patients do develop symptoms despite the presence of collateral arteries, frequently presenting with a variety of abdominal symptoms including nausea, vomiting, postprandial epigastric pain, and weight loss [61]. Over the years, several different interventions have been proposed for symptomatic MALS using different approaches such as open surgery, laparoscopic surgery, endovascular angioplasty, or hybrid procedures combining laparoscopic and endovascular techniques [60]. Surgical release of the extrinsic compression caused by the median arcuate ligament remains the mainstay of therapy, with overall success rates ranging from 53 to 79% and a majority of patients reporting rapid postoperative symptom relief [62].

In more recent years, the robotic approach has been gaining popularity due to its technical advantages over conventional laparoscopic surgery. In 2007, Jaik et al. were the first to report a robotic-assisted MALR [63]. Since then, several other case series have been published. In a case series of 13 patients, Khrucharen et al. analysed outcomes symptomatic patients undergoing robotic-assisted MALR. The authors found that robotic-assisted MALR is safe and feasible in selected patients and may be associated with reduced operative times [61]. In a follow-up study by the same group, laparoscopic and robotic-assisted MALR were compared for short- and intermediate-term clinical outcomes. In their retrospective study, a total of 34 patients were included (16 laparoscopic and 18 robotic cases) for further analysis.

Complete pain resolution was achieved in 37.5% in the laparoscopic group and in 44.4% in the robotic group ($p = 0.93$). The data showed no difference between conversion rates to open surgery, symptom recurrence rates, postoperative pain, and overall clinical improvement. However, median operative time was significantly shorter in the robotic group compared to the open group (179.5 versus 106 minutes, $p < 0.001$). The authors concluded that both laparoscopic and robotic-assisted MALR offer similar short- and intermediate-term outcomes, with a possible shorter operative time achievable by a robotic-assisted approach [64]. In another recent retrospective study by Fernstrum et al., 27 patients that underwent robotic MALR were included for analysis. Long-term improvement or resolution of symptoms and symptom recurrence was used as primary outcome. Their data showed mean operative times of 95 minutes and two cases of conversion to open surgery. Only one major complication occurred, which was an inadvertent arteriotomy of the celiac trunk that occurred while dividing a portion of the diaphragmatic fibres. After more than 30 days follow-up, 68% of patients had full symptom relief and 4% had partial symptom resolution. Furthermore, 4% of patients had no symptom resolution and 24% had symptom recurrence after an initial period of symptom resolution. The authors concluded that robotic MALR is a safe option for treatment of MALS with high-response rates [65].

3.2 Vascular bypass surgery

Aortoiliac occlusive disease (AIOD) can result in symptoms such as claudication and critical ischemia of the lower extremities. Generally, AIOD is treated by either endovascular or open surgery, depending on the severity and location of the occlusion. Whereas for extensive AIOD patients are generally treated using an open approach, endovascular approaches with covered stents have also been introduced with success using the 'covered endovascular reconstruction of aortic bifurcation (CERAB) technique [66]. The main disadvantage of endovascular repair are the high costs for the patient, insurance companies or hospitals [67]. An alternative for open surgery or endovascular therapy is a laparoscopic reconstruction [68]. A number of laparoscopic techniques for treating AIOD have been developed over the last few years with the aim of reducing operative trauma and achieving faster postoperative recovery rates. However, performing laparoscopic aortic surgery and vascular anastomoses is very challenging and requires intensive training [69]. More recently, robotic-assisted approaches have been developed in order to overcome these limitations of the conventional laparoscopic approach. In a retrospective case-series by Jongkind et al., a total of 28 patients that underwent robotic-assisted laparoscopic surgery (RALS) for AIOD were included. In this group, 24 patients received robotic-assisted laparoscopic aortobifemoral bypass grafting and 4 patients received an aortoiliac endarterectomy. Their results showed a median operative time of 350 minutes and median aortic clamping time of 70 minutes. In 4 patients, conversion to open surgery was necessary. One patient died within 30 days postoperatively and 4 patients had non-lethal complications. The authors concluded that RALS is a feasible and durable technique for treating patients with AIOD [70].

Other studies and case series have found similar clinical outcomes and complication rates. In another relatively recent retrospective study, 310 patients that underwent robotic-assisted vascular surgery were included for analysis. In this patient population, 224 patients underwent robotic-assisted surgery for treatment of occlusive disease, which included robotic ilio-femoral bypass, aorto-femoral bypass, and aorto-iliac thromboendarterectomy with prosthetic patch. Median clamping time and anastomosis times were 37 and 24 minutes, respectively. Mean total operative time was 194 minutes. In 2 cases (0.9%), a conversion to open

surgery was necessary. Lastly, median hospital LOS was 5 days. The authors concluded that the greatest advantage of these robotic-assisted procedures was the speed and relative ease with which vascular anastomoses could be performed [9]. This offers significant benefits regarding temporary lower limb ischemia times during aortic clamping. Despite the lack of large-scale clinical studies, the currently available data suggests that robotic-assisted approaches can play a significant role in treating arterial occlusive disease. These robotic approaches can even be combined with endovascular or open approaches into hybrid procedures, thus making it a versatile and potentially useful tool for the modern vascular surgeon.

3.3 Aortic aneurysm surgery

One of the greatest paradigm shifts towards MIS in the last decade has taken place in the field to the of aortic aneurysm surgery. With the introduction of endovascular approaches, the number of open aneurysm repairs has decreased dramatically, having steadily been replaced by endovascular aneurysm repair (EVAR) [71, 72]. Nevertheless, for patients that do not qualify for endovascular repair or with complications following endovascular repair, surgical repair of the aneurysm is often necessary. For this subset of patients, a minimal invasive approach may be an appealing alternative to the conventional open repair. Although laparoscopic techniques have been described for aortic aneurysm repair, this approach remains somewhat unappealing to many surgeons due to the steep learning curve [71]. Another possibility is the robotic-assisted approach for aneurysm repair, which is able to overcome the kinematics limitations of laparoscopy. Previous retrospective studies and case series have already shown the feasibility of the robotic approach for several types of aortic aneurysm repairs.

In a study by Stadler et al., 65 patients that underwent robotic-assisted aorto-iliac aneurysm surgery were included in a retrospective analysis of outcomes after robotic-assisted vascular procedures. Median operative time and aortic cross clamping time were 253 and 93 minutes, respectively. Overall mortality was 1.6%, median conversion rate was 13%, and no major non-lethal postoperative complications were noted. Furthermore, median hospital LOS was 7 days. The results regarding operative times and outcomes are similar to the conventional open repair technique, with the added benefits of MIS [9]. In addition to this, robotic-assisted surgery could also have a specific role in type-II endoleaks, the most frequent complication after EVAR. Currently these types of leaks are treated with surgical ligation or endovascular embolization, the latter being the first-line treatment option. However, endovascular embolizations of endoleaks has high recurrence rates. With the robotic approach, these endoleaks can be repaired more easily than with a laparoscopic approach, while simultaneously providing a more definitive solution for the endoleak. Morelli et al. showed that this technique is feasible in their recent case series [73].

4. Costs of robotic surgery

Despite the increasing popularity of robotic-assisted approaches worldwide, concerns have been raised regarding the high costs of acquiring and maintaining robotic systems [16]. In addition, stapling devices in robotic surgery often come at a high price, necessitating many centres to use standard manual or electronic stapling devices by the table surgeon instead of the console surgeon. Several studies have attempted to perform cost-analysis studies of robotic surgery compared to open and laparoscopic/thoracoscopic approaches. However, there are often significant

discrepancies between these studies, mainly due to different definitions of cost (console and robot; maintenance; instruments; stapling devices) and differences in healthcare and insurance regulations between countries [10]. A large-scale analysis of the NIS database showed that median costs of RATS were significantly higher than conventional VATS [74]. Similar findings were reported in an analysis of the Premier registry by Swanson et al. However, there is evidence to suggest that RATS is comparable or even less expensive than open surgery, mainly due to reduced operative times and shorter hospital LOS [75]. Furthermore, previous studies have shown that as programmes adopt and perform more robotic operations, the overall costs of hospitalisation will decrease [71]. These costs will likely decrease even more over time with the introduction of upcoming competitors' surgical robotic platforms [1].

5. Ergonomics of robotic surgery

In addition to the patient-related benefits of robotic surgery, these robotic platforms allow for a more ergonomic working environment for the surgeon [16]. Previous studies have already shown that work-related musculoskeletal disorders are frequently encountered among surgeons and surgical residents [76]. This is a result of several factors, such as frequent repetitive movements of the trunk and upper extremities and prolonged static body positioning [77]. When these work-related musculoskeletal disorders are not corrected early on, they can result in injuries such as carpal tunnel syndrome, wrist tendonitis, chronic back and knee pain, TOS, and the development of varicose veins [76, 78]. Several studies have compared conventional laparoscopic and robotic approaches and have found that surgeons using robotic surgery report less overall pain [79, 80]. In addition, data has shown that ergonomic training courses for surgeons can also significantly reduce pain [77]. However, more robust data from larger studies are necessary to measure the effect of robotic surgery on ergonomics, and physical and mental fatigue compared to conventional approaches.

6. Future of robotic surgery

Since the introduction of robotic-assisted surgery, surgeons and medical engineers have continuously searched for new technologies and advancements across all surgical fields. Since its introduction approximately 20 years ago, the da Vinci robotic surgery system (Intuitive Surgical Inc., Sunnyvale, CA, USA) has been involved in over 5 million operations, making Intuitive Surgical the largest player in the surgical robotic market [81]. However, with the original da Vinci patents now expiring, many medical 'tech' companies are now setting their sights on joining this lucrative, growing market. New systems in the near future will likely aim to improve on the current robotic models by incorporating new technologies such as single-port instrumental arms, haptic feedback, eye-movement tracking, and virtual reality (VR) [82]. In addition to the technological aspects of the current robotic systems, there are also some important practical limitations that can be improved upon, such as the high operational costs, the size of the robotic systems, and its accessibility in lower-income countries. Several "large" robotic systems have become available in the last few years. Some examples are the Senhance console (TransEnterix, Morrisville, NC, USA), BITRACK system (Rob Surgical, Barcelona, Spain), and the Revo-i surgical robot (Meere Company, Seoul, South Korea). These systems each have some advantages over the da Vinci system, such as haptic feedback or eye-tracking, but are generally limited by their price and large size [81].

In addition to these large systems, many companies have started to create smaller, more portable systems that allow more flexibility in hospitals that do not have robot-dedicated operating rooms. Perhaps the most daring and revolutionary concept that is entering the field of surgery is the surgical microrobot. Microrobot surgery is fundamentally different to the current robotic systems as it is not physically tethered to a console. These microbots can be propelled externally via electromagnetic fields or ultrasonographic energy, or internally using chemical reactions. Recent proof-of-concepts have shown that these microbots are able to perform various surgical manoeuvres such as dissecting, grasping, and ablation at a micro-scale [83–85]. Undoubtedly, the future of robotic surgery looks exciting as many new technologies are emerging at an exponential pace. The COVID-19 pandemic has shown an unprecedented demand of surgical robotic systems as well, mainly due to their ability of providing an additional shielding layer between the healthcare worker and the patient [86]. It is likely that this demand will outlast the pandemic itself and propel the development of surgical robotic technology.

7. Conclusion

It is without a doubt that robotic surgery has changed the surgical world over the last decade. An increasingly large group of surgeons are incorporating robotic approaches in their daily practice as more and more data has shown the benefits of these approaches. In thoracic surgery, RATS has proven to be a valuable tool for many oncological and non-oncological indications, resulting in it being considered one of the standard treatment approaches in many centres. Similar, although less prominent, trends are being noted in the field of vascular surgery as well. However, despite these promising future perspectives, there is still a lack of well-powered, multi-centre randomised trials comparing robotic approaches to open surgery or conventional laparoscopy/thoracoscopy. Furthermore, more data regarding the cost and cost efficiency of robotic surgery are necessary in order to determine whether the benefits of robotic-assisted approaches outweigh its costs.

Conflict of interest

The authors declare no conflict of interest.

Author details

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