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REVIEW

Robot-assisted vascular surgery: literature review, clinical applications, and future perspectives

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Abstract

Although robot-assisted surgical procedures using the da Vinci robotic system (Intuitive Surgical, Sunnyvale, CA) have been performed in more than 13 million procedures worldwide over the last two decades, the vascular surgical community has yet to fully embrace this approach (Intuitive Surgical Investor Presentation Q3 (2023) https://investor.intuitivesurgical.com/static-files/dd0f7e46-db67-4f10-90d9-d826df00554e. Accessed February 22, 2024). In the meantime, endovascular procedures revolutionized vascular care, serving as a minimally invasive alternative to traditional open surgery. In the pursuit of a percutaneous approach, shorter postoperative hospital stay, and fewer perioperative complications, the long-term durability of open surgical vascular reconstruction has been compromised (in Lancet 365:2179–2186, 2005; Patel in Lancet 388:2366–2374, 2016; Wanhainen in Eur J Vasc Endovasc Surg 57:8–93, 2019). The underlying question is whether the robotic-assisted laparoscopic vascular surgical approaches could deliver the robustness and longevity of open vascular surgical reconstruction, but with a minimally invasive delivery system. In the meantime, other surgical specialties have embraced robot-assisted laparoscopic technology and mastered the essential vascular skillsets along with minimally invasive robotic surgery. For example, surgical procedures such as renal transplantation, lung transplantation, and portal vein reconstruction are routinely being performed with robotic assistance that includes major vascular anastomoses (Emerson in J Heart Lung Transplant 43:158–161, 2024; Fei in J Vasc Surg Cases Innov Tech 9, 2023; Tzvetanov in Transplantation 106:479–488, 2022; Slagter in Int J Surg 99, 2022). Handling and dissection of major vascular structures come with the inherent risk of vascular injury, perhaps the most feared complication during such robotic procedures, possibly requiring emergent vascular surgical consultation. In this review article, we describe the impact of a minimally invasive, robotic approach covering the following topics: a brief history of robotic surgery, components and benefits of the robotic system as compared to laparoscopy, current literature on "vascular" applications of the robotic system, evolving training pathways and future perspectives.

Keywords Robotic surgery · Vascular robotics · Laparoscopic surgery · Vascular surgery · Robotic-assisted laparoscopic vascular surgery

Introduction

The robotic-assisted laparoscopic approach has transformed many surgical subspecialties; however, it has yet to gain momentum and play a central role in vascular surgery [1–4]. Other surgical specialties such as thoracic surgery, general surgery, and urology have embraced robotic technology into clinical routine and now providing minimally invasive surgical options to patients while mastering the vascular skill sets imperative for these procedures. In the meantime, endovascular surgery has revolutionized the field of vascular surgery, delivering the promise of minimally invasive therapeutic options to our patients. However, one could argue that the durability of open surgical vascular reconstruction and repair has been compromised, in this pursuit of percutaneous endovascular technologies, as evidenced by the re-intervention rates for endovascular procedures [5–7]. The lack of early adoption of surgical robotics could be potentially due to the lack of surgical laparoscopic skills/training among vascular specialists, fear and risk of uncontrolled bleeding, and

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the inherent difficulties of creating laparoscopic vascular anastomosis.

A surgical procedure can be broadly divided into two parts: firstly, the core therapeutic part (i.e., the only portion which the patient benefits from) and secondly, the delivery system—the part that provides access/conduit to deliver the intended core therapeutic option. For example, to sew in a piece of Dacron into the aorta—as initially described by Dr. DeBakey—is easily the most durable repair described for aortic aneurysmal disease [8]. However, the delivery system—either a laparotomy thoracotomy or thoracoabdominal incision is very unappealing to most patients and associated with higher perioperative complication rates than endovascular alternatives [9]. Endovascular aortic repair has a very appealing delivery system namely a small incision or puncture site, however, the core therapeutic part of stent graft placement is fraught with long-term problems and is nowhere near the durability of the Dacron-based vascular reconstruction for abdominal aneurysmal disease [8, 9]. These endovascular procedures also became an early target for steerable, robotic catheter technology; however, its routine adoption has been limited and also redirected recently toward image-guided, robotic endobronchial interventions, where it is transforming diagnosis and therapeutic care for patients with malignant lung nodules [10–12].

The concept that the robotic approach is an equivalent of an open operation delivered with a minimally invasive technique, due to the dynamic wristed instruments, which are essentially mimicking the hand movements of a surgeon, inside the body, makes it dramatically different from the traditional laparoscopic approach. An intriguing question is whether robotic surgery introduced in the vascular surgery world could retain the core therapeutic components that have been validated for decades while at the same time making the delivery of such repairs more acceptable and tolerable to patients. It is this intriguing concept that stimulated us to evaluate the role of robotics.

The outline of this review article is as follows: a brief history of robotic-assisted vascular surgery, components and benefits of the robotic system as compared to laparoscopy, current literature on vascular applications of the robotic system, evolving robotic training pathways of vascular surgeons and future perspectives of robotic vascular surgery with novel techniques/instrumentation.

Brief history of robotic surgical platforms

Early surgical robots were specialty focused, like the Robodoc, which was first developed in the late 1980s, for orthopedic surgery, or another urologic robot—developed for prostate surgery. Later advancements were propelled by the US military, which wanted to develop a telemedical unit that could provide surgical care in close proximity of the battlefield, operated by a surgeon in the safe zone. This led to the pioneering development of the Green Telepresence System, which consisted of a surgeon's workstation and a remote surgical unit. This robot laid the basis for today's surgical robotic appliances. Although it was first developed for open surgery, only after one of the developers, Colonel Satava, saw the presentation of Dr. Perrisat on one of the first videotaped laparoscopic cholecystectomy, the system was transitioned toward laparoscopic surgery. Interestingly, the first procedures that have been tested on robotic surgical systems were mostly vascular operations, such as running suture on bovine aorta, patch angioplasty, and PTFE graft anastomosis with the contribution of Jon Bowersox, a vascular surgeon from the Stanford Medical Center. They were all successful attempts, but were significantly slow, due to the lack of wristed instruments in early robots that were only introduced in the mid-1990s. Along with the above-mentioned efforts of the Stanford Research Institute and the Defense Advanced Research Projects Agency (DARPA), two private companies, Computer Motion and Intuitive Surgical, raced for the development of the ultimate surgical robotic system. Their competition ended with merging in 2003. Computer Motion's Zeus system was discontinued for the sake of Intuitive Surgical's more versatile robot, the da Vinci. The prototype of the da Vinci surgical system—called Lenny, was developed in 1995. It had to be attached to the surgical table and had fixed instrumentation. Later with the introduction of exchangeable instrumentation, Mona was developed, and was first used in human trials in 1997. It lacked a camera holding arm, so an assistant had to be present manipulating the camera on the instructions of the operating surgeon. Further improvements in visualization and the addition of a stand-alone cart—housing the patient-side components, were revealed one year later, forming the first surgical robot with the name da Vinci. After successful human trials, it received FDA approval in 2000 for general surgery indications in the USA [13, 14]. Since then, the surgical robot has gone through significant upgrades and now represents state-of-the-art technology (Fig. 1).

Intuitive Surgical reported that by September 2023, more than 13 million procedures were performed on the da Vinci system. More than 8200 da Vinci robots are available worldwide. The industry is exponentially growing and mostly led by general surgeons, urologists, and gynecologists, while other specialists, including vascular surgeons, only take part in a small fraction of procedures performed [1]. However, many of these procedures include essential vascular techniques, most vascular surgeons are yet to receive training on the robot. It is not only problematic in terms of practicing vascular operations, but also when it comes to treating rare, life-threatening vascular complications using the same robotic platform.

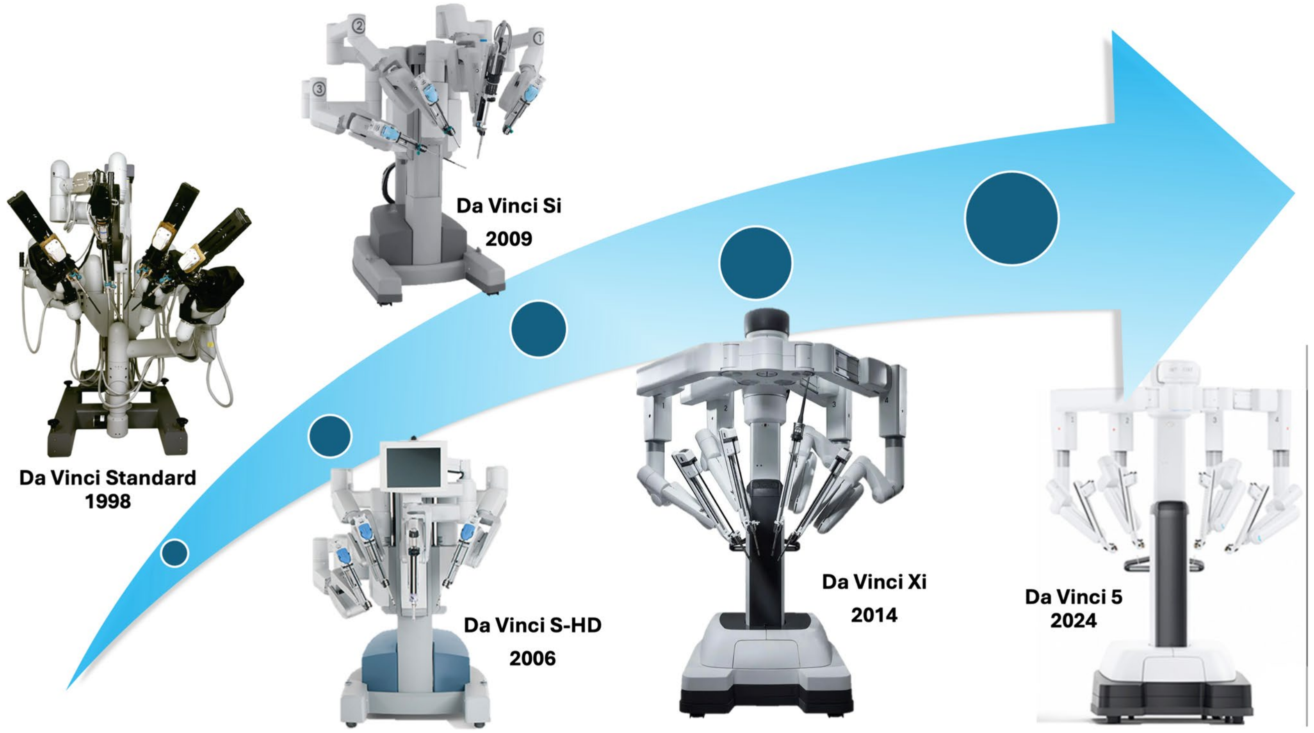

Fig. 1 Evolution of Intuitive Surgical's da Vinci Surgical Robot (Intuitive Surgical, Sunnyvale, CA, USA)

Introduction to the da Vinci surgical robotic system

The most used laparoscopic robot, the da Vinci system can be subdivided into three subsystems, namely the surgeon console, the patient-side cart, and the vision cart. The surgeon who is performing the operation is physically disconnected from the patient, sitting in an ergonomic control unit, controlling a master–slave teleoperation architecture with an intermediary of a computerized control system. The patient-side manipulators are mounted on the transportable patient-side cart. The robot has four arms that work in the sterile field. Each of these can hold either an endoscopic camera or a surgical instrument. Since the input by the surgeon runs through a computer, it can filter out unwanted signals, such as the tremor of the surgeon's hand, or it can scale motions to facilitate enhanced precision when it is required. But it could go both ways: the robot could inform the surgeon, based on visual or other imaging clues—aiding orientation, giving warning signs on critical steps, and ultimately enhancing patient safety. Certainly, it is the topic of the future, and innovation has limitless potential in this field [15].

Also contributing to better orientation, the state-of-the-art visualization system offers 3D vision by a stereo endoscopic camera that records in 4 K resolution [16].

Since the most widely available robotic systems do not support haptic feedback, one of the most important perceptions is lost. This forms huge limitations in vascular procedures, where tactile feedback is often paramount. However, in March 2024, Intuitive Surgical revealed the new, fifth-generation da Vinci robotic system, which will support haptic feedback, a long-awaited feature in robotic surgery. With this, tissue handling, and possibly suture handling, will improve. One of the hardships of today's robotic instruments is that they can break monofilament sutures like Prolene (Ethicon, Raritan, NJ, USA) very easily, due to handling by the needle drivers, which is why most vascular robotic surgeons use PTFE sutures which are proven to be a bit more durable.

The biggest advantage of robotic surgery in contrast to laparoscopy is the utilization of wristed instruments that can be operated in an ergonomic and intuitive manner. These articulated instruments can allow up to seven degrees of freedom including grasping. These can essentially act as an extension of the surgeon`s arm, allowing a wide range of motion.

In the fourth-generation da Vinci system, visual clues help to overcome the lack of tactile feedback. As opposed to open vascular procedures, where one of the key techniques of locating blood vessels is palpation, on the robotic platform, localization mostly relies on visual clues. One of the existing imaging technologies that could help in the visualization of blood vessels is FireFly®—which is a near-infrared fluorescence imaging technology, where with the intravenous injection of indocyanine green, blood vessels can be highlighted [16].

The da Vinci Xi robot can be synchronized with the TRUMPF Medical TruSystem 7000dV operating table (TRUMPF Medezin Systeme, Saalfeld, Germany), which allows the surgical team to move the table without redocking the robot. The robot automatically adjusts the gantry and instruments to maintain position relative to the patient`s anatomy. This provides more efficiency and optimal exposure during multi-quadrant operations [16].

Currently, the most widely used robotic surgical system is represented by the da Vinci Xi robot, which was introduced in 2014. Compared to the previous model—the Si, it offers several advantages. It comes with an endoscopic camera that fits in an 8 mm port and supports 4 k resolution and 3D vision with magnification. A significant improvement over the previous generation is that the endoscope can be mounted on either of the robotic arms, which creates more freedom for port placement. If using the 30-degree optics, the surgeon can flip the camera 180 degrees with a simple touch of the touchscreen, without having the assistant do it manually. The touchscreen on the surgeon console can control the electrocautery and several other functions can be adjusted on the go. The patient-side cart's top-mounted rotating boom enables multi-quadrant surgery without having to redock the robot. Laser guidance helps the faster docking process. The autotarget function optimizes the position of the robotic arms—which are significantly sleeker and can reach further, so they can move more freely without colliding. A synchronizeable table—as mentioned before, enables table movements during the operation without the need for redocking. All these advancements create a much more intuitive and user-friendly platform than laparoscopy. Along with the technical details, there is great emphasis on training, which in the case of the robotic system can be performed in computer simulation in a structured manner through Intuitive Surgical's Learning platform.

Advantages and disadvantages of the robotic surgical platforms

The advantages of robot-assisted surgery include the capability of 3D visualization, seven degrees of freedom provided by the Endo-wrist technology, elimination of the fulcrum effect, and physiologic tremors. It also has the ability to scale motions and even to perform telesurgeries if needed. The system allows the surgeon to take up a more ergonomic posture than what traditional laparoscopy would require [17, 18]. Although sitting in front of the surgeon console is considered more ergonomic, it has its challenges, like the possible development of upper body fatigue and neck pain; therefore, the correct use of the armrest and individual adjustment of the seating position is important [19].

One of the main drawbacks of the robotic approach is the lack of tactile or haptic feedback, which is present in laparoscopy. The system requires additionally trained staff to operate and a large enough space for the equipment [17]. Finally, its long-term outcome benefit is yet to be proven in vascular surgery. Today, only relatively small single-center studies and case series have been published.

A significant limitation of the widespread adoption of robotic surgery is its high cost. The price makes the equipment inaccessible to most hospitals, not to mention the high annual maintenance fees and additional cost of disposable instruments. Its use is generally limited to centers, although it's sensible, considering the need for high expertise, which can be gained only through a high volume of cases. However, cost issues could be counterbalanced by reduced length of stay, lower morbidity, and better surgical outcomes as reported in urology and colorectal surgery compared to other techniques [20, 21].

Besides the most widespread da Vinci robotic system, several other—possibly more cost-effective—robots are either under development or undergoing clinical trials to compete with the current generation. These could eventually create healthy competition in the market leading to lower costs and urging innovations [22].

In 2010, Stefanidis et al. highlighted the intuitive nature and steep learning curve of robotic procedures with their experiment involving 34 medical students with no prior laparoscopic or robotic experience. They performed suturing tasks using laparoscopy and the da Vinci robot on a live porcine model. Results showed faster suturing, higher assessment scores, and fewer errors per knot with the robot. Laparoscopic performance did not significantly improve over rounds, while robotic assistance led to significant improvement [23].

Challenges in the adoption of surgical robotic technology in vascular surgery

The da Vinci Surgical System is approved for cardiac, thoracic, urologic, gynecologic, otorhinolaryngologic, colorectal, and general surgical uses. Despite numerous robotic procedures involving core vascular surgical techniques, the vascular application is still considered off-label [3]. The question is why did most vascular surgeons neglect this technology?

Every surgical specialty aspires to find less invasive ways to treat patients. Vascular surgery is no exception. We use vasculature as a pathway to reach and fix the disease with wires, catheters, balloons, and stents. Endovascular techniques have evolved in such a way, that in many areas of vascular surgery, it became the primary choice of care [24–27]. Most notably in cases of aortic aneurysmal disease or aortoiliac occlusive disease (AIOD), endovascular techniques offer less perioperative mortality, shorter hospital stay, comparable long-term durability, and survival. Despite these important factors, endovascular procedures often come with an increased re-intervention rate, and the need for lifelong surveillance, not to mention the elevated costs [5, 6, 28].

Recent studies have pointed out that the better long-term durability and need for less invasive surveillance methods and decreased exposure to radiation because of frequent CTA scans may outweigh the higher perioperative morbidity of open abdominal aortic aneurysm repair, also providing a better quality of life [6].

Not every patient is fit for open repair, even so in the case of most of the typical population requiring vascular surgery. These patients often have multi-systemic disease, limiting their ability to endure the surgical stress of an open reconstruction, subsequently suffering from high perioperative morbidity and mortality. Besides the possibility of endovascular interventions, robotic reconstruction could be the third operative option to choose from.

The failure of the adoption of laparoscopy in vascular surgery

Although laparoscopic aortic surgery has been available for more than 20 years, only a handful of centers have adopted the technique. The main reasons for it include the lack of interest, focus on endovascular treatment options, required steep learning curve, and most notably the difficulties of creating a vascular anastomosis, subsequently longer clamping times, and prolonged operation times [3]. Vascular surgical laparoscopy is extremely difficult to master.

Apart from technical difficulties, the laparoscopic approach could retain most of its attributed benefits when used for vascular reconstructions. A comparative study between open abdominal aortic repair and total laparoscopic repair found that there was no significant difference in short-term morbidity and mortality, but with laparoscopy, the operative times were significantly longer, mainly due to a longer anastomosis creation time. Interestingly, more bleeding was observed in laparoscopic cases [29]. This could be accounted for by several problems, such as the lack of effective tamponade, the negative effect of suction on the pneumoperitoneum, and consequently the loss of visual control. Possibly, the most feared complication of laparoscopy is major vascular injury, which can lead to severe complications, even death of the patient. Perhaps the lack of safe vascular control, mostly derived from the lack of appropriate laparoscopic clamps, was one of the main aversive factors against laparoscopy for the vascular community. This issue is still present in robotic surgery, which is why the development of reliable dedicated robotic vascular instruments is essential for the ability to perform more arterial cases with the robot.

The laparoscopic technique was associated with benefits including shorter hospitalization, reduced need for pain medication, and reduced time of postoperative bowel dysfunction [29]. Long-term results of laparoscopic aortic reconstruction yielded comparably good results to open repair in terms of survival and need for re-intervention, but with the additional benefit of the lack of laparotomy-related complications [30].

Despite the above-mentioned results, originating from only a handful of centers worldwide, laparoscopy was not appealing enough for vascular surgeons to invest in, due to inherent technical difficulties and the lack of laparoscopic training in vascular surgical education.

Although the robotic approach is based on the fundamentals of laparoscopy, it is a dramatically different technique. The main difference lies in the wristed robotic instruments and intuitive controls that facilitate surgical manipulation, resulting in shorter learning curves, allowing for faster vascular anastomosis and consequently shorter clamping times [31].

Current vascular procedures performed with robotic assistance

The following section describes vascular procedures currently performed using the da Vinci system. In terms of procedural volumes, most of these are performed by non-vascular specialists, who have mastered essential vascular surgical skills with the use of the robot. We believe that there are many techniques to be learned from these specialties, to adopt this technology in the vascular field. (Table 1).

Robot-assisted infrarenal aortic and aortoiliac aneurysm repair

Performing aortic reconstruction requires the ability to control high-pressure arteries, often heavily calcified. Choosing the right place for clamping heavily relies on preoperative imaging, as haptic feedback is unavailable (except the latest-generation da Vinci robot), although there are some visual clues like the color of the vessel wall or how it reacts to movement and palpation with the instruments, which might help the decision. Clamping can be done either by inserting a laparoscopic clamp through an assist port or by inserting a DeBakey clamp through a small incision. Balloon occlusion of the iliac arteries can be performed as well. However, we have to point out that no specialty-focused vascular robotic instruments, like dedicated aortic robotic clamps, are available so far.

Table 1 Vascular procedures performed using the da Vinci robotic platform across different surgical specialties

	Robotic vascular procedures	Surgical specialty
1	Infrarenal aortic aneurysm repair	Vascular surgery
2	Aortoiliac reconstruction	Vascular surgery
3	Thoracofemoral bypass	Vascular surgery
4	Treatment of type II endoleak after EVAR	Vascular surgery
5	Splenic artery aneurysm repair	Vascular surgery
6	Median arcuate ligament release	Vascular surgery
7	Left renal vein transposition	Vascular surgery
8	IVC filter removal	Vascular surgery
9	First rib resection	Thoracic surgery, Vascular surgery
10	Nephrectomy and IVC thrombectomy	General surgery, Urology
11	Kidney transplantation	General surgery
12	Lung transplantation	Thoracic surgery
13	Pancreaticoduodenectomy with portal vein reconstruction	General surgery
14	Totally endoscopic coronary artery bypass (TECAB)	Cardiac surgery

Identification and control of lumbar arteries before opening the aneurysm sac is another key element in the safety of these operations, as uncontrolled bleeding from these can cause major issues. Preoperative imaging and image fusion could play a major role in this topic. There is an extensive need for further research in this regard.

Despite these concerns, Stadler and Lin have published case series with successful surgeries and acceptable operation times, when compared to laparoscopy, with improved clamping times and tolerable bleeding [32–36]. The latest report from Dr. Stadler included 61 patients operated on for aortoiliac aneurysms. The median operation time was 253 min (range, 185–360), the median clamping time was 93 min, and the anastomosis time was 31 min. Conversion to laparotomy was required in eight cases (13%), and median blood loss was 1210 ml. The median hospital stay was 7 days [36]. Although reported numbers prove that robot-assisted reconstruction is feasible and can be performed with good results, most of the studies come from a few centers and a relatively small number of cases. Further studies are needed to assess the place of robotic surgery in this field as well as to prove whether it has comparable results to open reconstruction and endovascular approaches.

Aortoiliac occlusive disease (AIOD)

There is extensive literature on the results of robotic aortic reconstruction with the indication of AIOD, but mostly from a few centers [36]. Wisselink and colleagues were the first to publish a successful aortobifemoral bypass with robotic assistance in 2002 [37]. Later, in 2009 Martinez et al. published the first totally robotic aortobifemoral bypass surgery [38].

Stadler reported the largest number of cases. During a nine-year period, 224 patients underwent robot-assisted reconstruction with the indication of AIOD. The median operation time was 194 (range, 127–315) min with a median clamping time of 37 min, of which the median anastomosis time was 24 min. Median bleeding was estimated to be 320 ml and the median length of stay was 5 days. According to pooled data including patients operated on aneurysmal disease, perioperative complications rate was 3% and 30-day mortality 0.3% [36].

In a recent study, early and midterm outcomes of robotic aortoiliac reconstruction were published. Out of 70 cases, conversion was required in three cases, two of which were because of bleeding complications. Early complications occurred in 14 cases, with 10 needing reoperation. Mortality was 1.4% (one out of 70 patients). Primary patency at 12 and 48 months was reported to be 94% and 92%, respectively, while secondary patency was 100% and 98.1% [39]. Although the above-mentioned results suggest that the operation is feasible and safe, and provides appropriate mid-term durability, it did not reach widespread acceptance; only a few centers made attempts with the technique due to partly technical problems such as missing dedicated vascular instrumentation or legal issues [39].

Furthermore, such as in the case of aortic aneurysms, in the case of AIOD, endovascular procedures have become more and more practiced with relatively low complication rates and acceptable durability, limiting the attention to other minimally invasive alternatives [40–42].

Robot-assisted thoracofemoral bypass

Thoracofemoral bypass has better patency rates than axillofemoral bypass, but requires a patient who can tolerate thoracic exposure and clamping of the descending aorta. By using robotic assistance, the time taken for the anastomosis can be shortened. However, this procedure is rarely done, due to the narrow group of ideal patients, and to the advances in endovascular therapy [43].

Robotic treatment of type II endoleak after endovascular aortic repair (EVAR)

Type II endoleak after EVAR can be a challenging diagnosis. Guidelines recommend re-intervention in the presence of sac enlargement during follow-up [24]. Most treatment options consist of endovascular techniques, but when these fail, open reconstruction may be required.

In a recent meta-analysis, results of eight studies, comprising 196 patients undergoing semiconversion (open conversion with endograft preservation), were analyzed. In 70% the indication was isolated type II endoleak. In 45.8%, previous endovascular attempts were made to close the endoleak. Aortic clamping was not necessary in 92% of the cases, but the sac was opened in 96%, and ligation or suture of the culprit arteries was performed. 30-Day pooled mortality was a non-negligible 5.3% with major systemic complications in 13.4% of the cases. Recurrence of endoleak was seen in 12.6%. Overall survival rate was 84.6% [44]. EVAR is generally considered a less durable, but minimally invasive procedure than traditional open repair, and thus offered to more frail patients or because of the intent to avoid high surgical risk. Where the reason for EVAR is to avoid complications associated with open repair, an open reoperation is a contradictory choice. When endovascular options fail, less invasive treatment can be provided by robot-assisted techniques.

There are a few small case series with robot-assisted surgery published on this topic. In 2009, Lin et al. presented a case, with successful robot-assisted ligation of the inferior mesenteric artery, which was the source of a type II endoleak, causing sac enlargement in an 84 old male. The total operation time was 249 min, of which 180 min was the time of robotic assistance. The estimated blood loss was only 50 ml. The patient tolerated the procedure well and was discharged home without complications on the 2nd postoperative day. The 3-month follow-up CT scan confirmed the occlusion of the IMA and the stabilization of the aneurysm sac size [45].

In 2019, Morelli shared their experience with their first two patients who underwent total robotic type II endoleak repair. They reported promising results. The average length of surgeries was 183 min, and average hospitalization was 2.5 days. The operation consisted of two phases: firstly, the ligation of the IMA and then the posterior mobilization of the aneurysm sac to make the selective clipping of lumbar arteries. Preoperative CTA imaging was used for the identification of feeding vessels in these cases. After target ligation was complete verification of the absence of backflow was carried out with a dedicated US probe, inserted through one of the assistant ports [46].

The above-mentioned literature shows that robot-assisted type II endoleak repair is feasible and safe, but more studies are required to evaluate its potential among other approaches. One of the biggest challenges lies in identifying the correct feeding vessels on preoperative imaging and translating this finding to the robotic platform. Creating an imaging-based navigation system, possibly with the help of augmented reality, could be an answer. Studies on how existing imaging can help intraoperative navigation and orientation are warranted.

Another challenge is finding an efficient method to expose both the left- and right-sided lumbar arteries, or the medial sacral artery, which often presents as a cause of endoleaks. The modified transperitoneal approach described by Stadler et al. is adequate for exposing the left-sided side branches, but going under an often heavily calcified aorta to reach feeding branches on the other side is a risky maneuver, which can easily result in bleeding complications requiring conversion [47]. Exposing the aorta from the right side is unlikely the answer to this dilemma due to the closeness of the inferior vena cava and the need for redocking and repositioning of ports, which would make the operation significantly longer and more complex. A hybrid approach mixing robotic exposure with endovascular techniques might present a solution, but this area is still in an experimental phase and needs further studies in terms of feasibility and safety.

Robot-assisted splenic aneurysm repair

Splenic artery aneurysm is the most common type of visceral aneurysm, with a prevalence of around 0.8% in the general population. Generally, diameters exceeding 30 mm are to be treated especially in pregnant women (regardless of the size) and symptomatic cases. The first treatment of choice if feasible is an endovascular procedure, but open reconstructions also provide viable options. Laparoscopic or robotic procedures could be proposed if the patient is not a candidate for endovascular treatment and open surgery predicts poor prognosis [48, 49].

Median arcuate ligament syndrome (MALS)

In median arcuate ligament syndrome compression of the celiac artery by the interweaving fibers of the two diaphragmatic pillars causes most typically postprandial epigastric abdominal pain, but can also be an incidentally found radiologic sign, often asymptomatic. Prevalence is 2/100,000 patients and it is more common in women, mainly affecting younger patients. Exclusion of other possible causes of abdominal discomfort is usually part of the evaluation [50]. Traditionally, the solution was carried out via open surgery, then laparoscopy emerged, offering a minimally invasive alternative. However, operating in tight spaces, the need for thorough clearance of the celiac plexus, controlling bleeding, or even performing vascular anastomosis made these surgeries challenging.

A few studies have presented small to medium amounts of cases of MALS release with robotic assistance. All reports show favorable outcomes and technical feasibility with minimal conversion rates and short in-hospital stays, providing good long-term results in terms of symptom relief and decrease of peak systolic velocity during ultrasound control. Re-interventions may be necessary in relatively small numbers [50–53].

In a recent case report, a patient who was not a candidate for open surgical reconstruction presented with pancreaticoduodenal and gastroduodenal artery aneurysm with celiac artery compressive occlusion. A three-step procedure was performed, where the robot-assisted release of the celiac artery was followed by stenting of the celiac artery and coil occlusion of the aneurysms [54].

Comparison of laparoscopic vs. robotic MAL release resulted in an equally effective decrease in measured PSV (peak systolic velocity) on duplex ultrasound postoperatively. Operative times were longer in the robotic group (mean of 86 min vs. 134 min). This could be attributed to the inherent mechanics of the robotic platform and the extended dissection performed in robotic cases. The latter could be associated with significant relief of postprandial symptoms and chronic nausea compared to laparoscopically operated patients. The authors also pointed out that robotic operations required significantly more junior first assistants and less frequently required second assistants, which can balance out the elevated costs of robotic equipment, while helping with the training of young residents [55] (Fig. 2).

Left renal vein transposition for nutcracker syndrome

Renal nutcracker syndrome is a rare phenomenon characterized by the compression of the left renal vein, causing diverse symptoms, but most notably flank pain, hematuria, pelvic congestion syndrome in women, or left varicocele in men [56]. Consensus on the standard treatment of this phenomenon has not yet been reached. Several treatment options include open surgical or laparoscopic transposition of the left renal vein, kidney auto-transplantation, endovascular procedures, and recently robot-assisted techniques [57]. Several small case series were published, reporting favorable outcomes with low complication rates and good clinical outcomes in terms of symptom relief [57–59]. However renal auto-transplantation, even with robotic techniques is not a complication-free procedure and requires careful patient selection and high level of experience [56]. (Fig. 3).

Robot-assisted IVC filter removal

Whereas the FDA (US Food and Drug Administration) recommends IVC filter removal once the risk of embolization is gone, the retrieval rate is only around 25–30% in the USA [60]. Endovascular approach is considered the first choice when an IVC filter is to be removed; however, sometimes these attempts are unsuccessful or considered high risk because of possible extrusion of the filer. Robot-assisted surgery can be an alternative to an open approach, providing a minimally invasive solution. Few case series have been published on robot-assisted IVC filter removal, each of which presents good results, with high success rate,

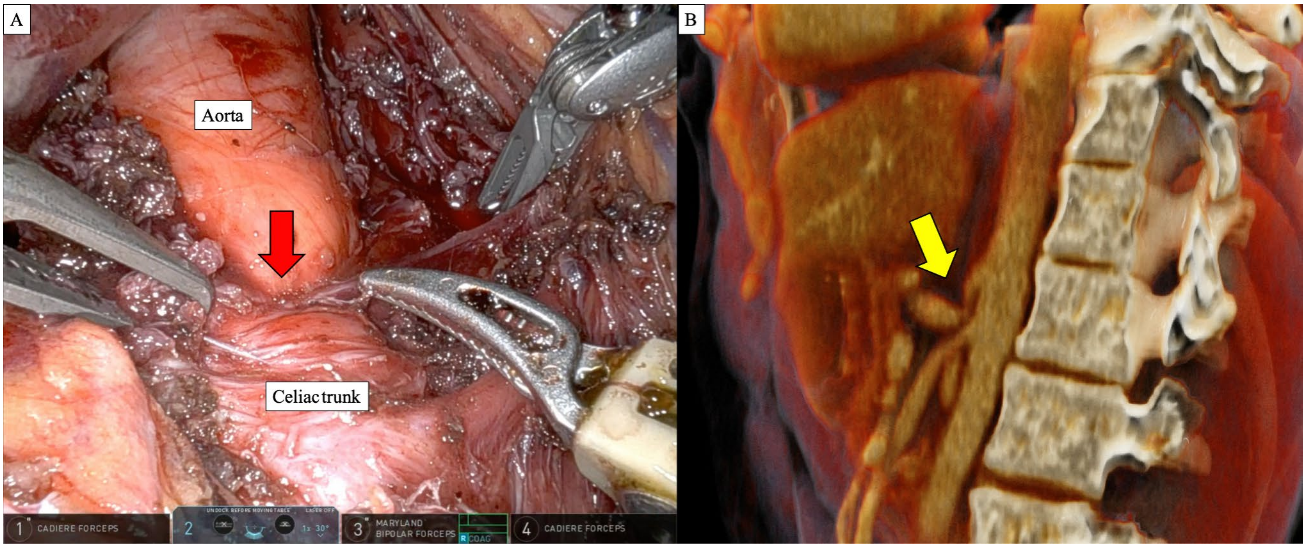

Fig. 2 **A** Intraoperative view of the median arcuate ligament (red arrow) causing a visible compression at the origin of the celiac artery. **B** 3D CTA reconstruction image of the same patient. The yellow arrow marks the compressed celiac artery

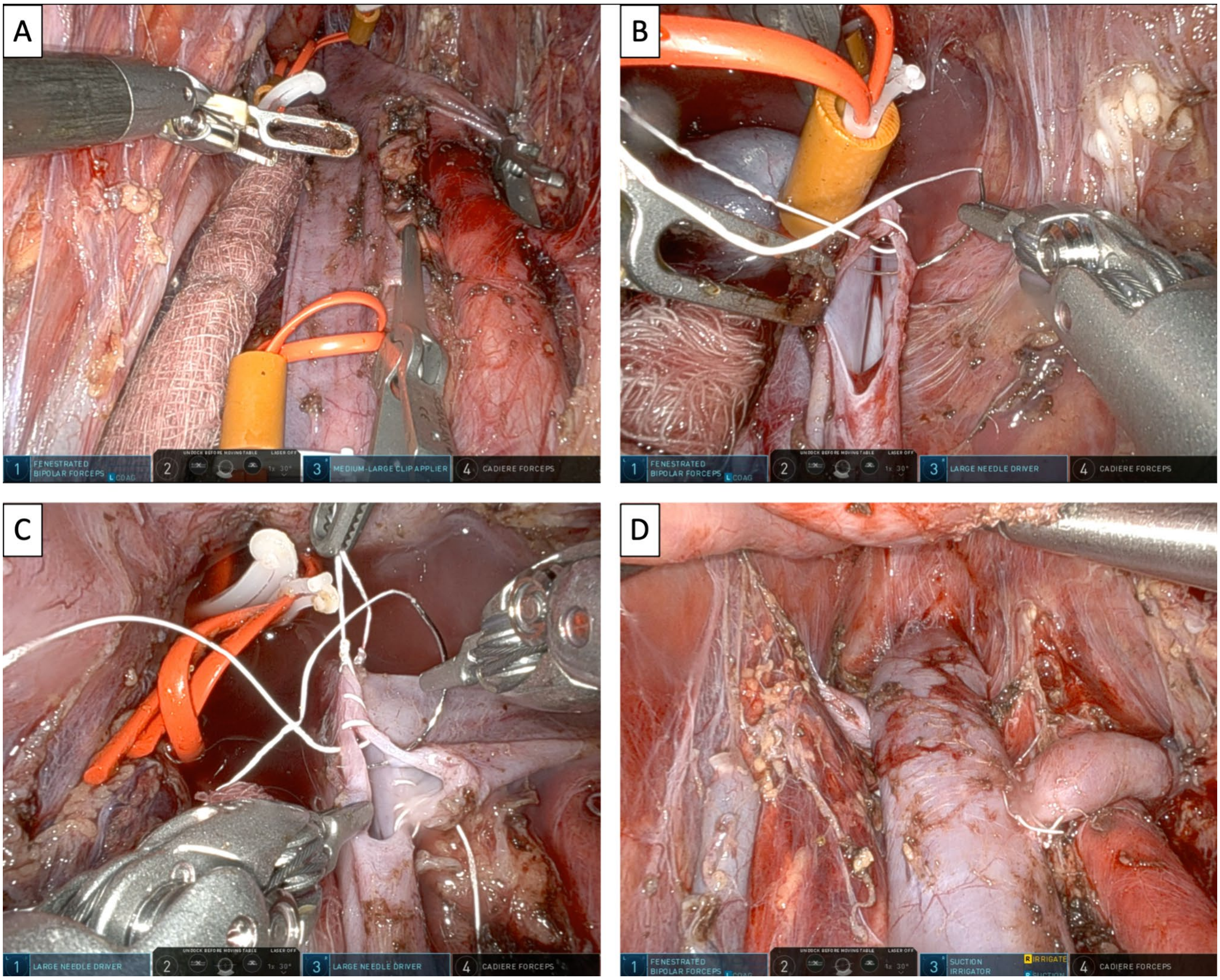

Fig. 3 Steps of a robotic renal vein transposition. **A** Rommel tourniquet on the supra- and infrarenal IVC, right renal vein, and laparoscopic bulldog clamp on the left renal vein and a lumbar vein. **B** Closing the defect of the IVC after the transection of the left renal vein. **C** Creation of the cavorenal anastomosis more distally. **D** Completed transposition of the left renal vein

low number of postoperative complications, and short length of stay [59, 61, 62] (Fig. 4).

Robot-assisted first rib resection

A case series of 83 patients undergoing robotic first rib resection with the indication of Paget–Schroetter syndrome was presented in 2018. The robot was used for the dissection of the first rib, disarticulation of the costosternal joint, and division of the scalene muscles. The operative time was 127 min (±20 min). Median hospitalization was 4 days, and no surgical or neurovascular complication was reported [63].

A systematic review comprising 12 studies of 379 patients with TOS suggested that the robotic technique is an effective method in the treatment of TOS. It offers improved exposure, reduced risk of neurovascular injury, and shorter hospitalization [64].

Robot-assisted nephrectomy and IVC thrombectomy

The gold standard technique of open radical nephrectomy with inferior vena cava (IVC) thrombectomy for renal cell carcinoma presenting with IVC thrombus is more and more challenged by a robot-assisted approach. Since the first published case series in 2011, a growing number of surgeons attempted to adopt the technique with a promise of an equally effective but less invasive approach [65]. While this procedure involves dissection and even opening of major vessels, it's mainly performed by urologists, who have mastered specific vascular surgical skills with the robot. In 2022, a meta-analysis evaluating robotic IVC thrombectomies

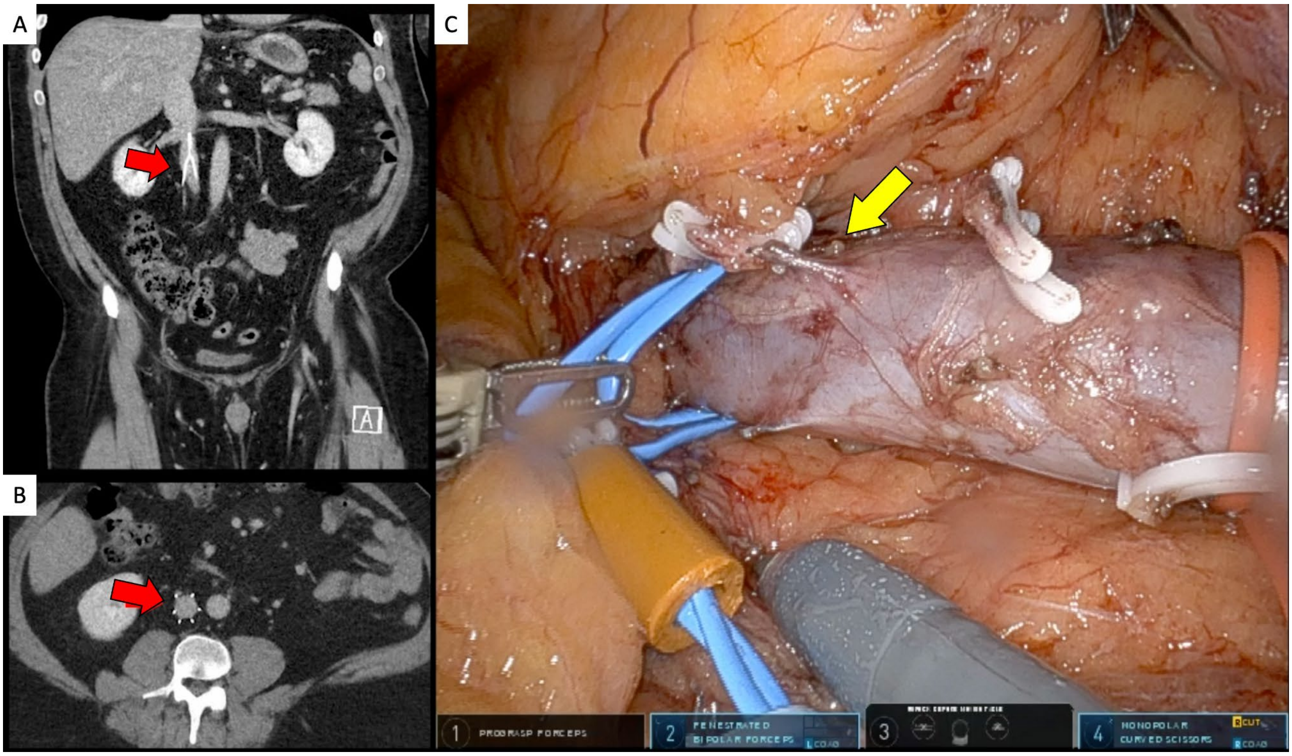

Fig. 4 Robot-assisted IVC filter removal. In picture **A** and **B** protrusion of the filter's struts can be appreciated on CT imaging, marked with a red arrow. **C** Intraoperative view of the infrarenal IVC with the protruding struts of the filter

versus open surgeries concluded that the minimally invasive method is feasible, effective, and safe. It is associated with fever perioperative complications, lower postoperative transfusion rates, and shorter in-hospital stays, although it is still a relatively infrequent procedure apart from a few high-volume centers. Most possibly this is due to the considerable complexity of these cases, involving manipulation of major vessels with a significant risk of major bleeding complications [66].

One of the main challenges of this operation is to acquire control over the main vessels. Temporary occlusion of the IVC can be done by clamps introduced to the abdomen through an assist port or simple stab incision. Another technique is to apply vessel loops circumferentially and then create a modified Rummel tourniquet using a small rubber tube. This can be later reinforced by the application of laparoscopic bulldog clamps.

Kundavaram et al. described a technique when the temporary occlusion of the IVC is obtained by an intracaval 9 Fr Fogarty catheter inserted through a 5 mm assist port into the abdomen. The IVC is punctured, the catheter is introduced, then inflated. The position of the balloon is either confirmed by laparoscopic ultrasonography or transesophageal echocardiography [67]. Later, this approach was modified by the insertion of a Reliant compliant balloon (Medtronic, Minneapolis, MN, USA) into the IVC through the right internal jugular vein under fluoroscopic and intraoperative ultrasonographic guidance [68].

Robot-assisted kidney transplantation

Open kidney transplantation is the gold standard of care in end-stage renal disease. Since first performed in 1954 by Doctor Joseph E. Murray, the technique has not changed much.

In the 1990s, advances in minimally invasive surgery warranted the adoption of these techniques in the field of transplant surgery. The first laparoscopic donor nephrectomy was reported by Ratner et al. in 1995, and not much later it gained widespread acceptance and has become the standard technique for kidney donation. Laparoscopy's adoption into renal implantation on the other hand was challenging. Since the first laparoscopic kidney transplant in 2009, it was rarely performed, because of the challenge of completing intracorporeal vascular anastomosis with instrumentation lacking articulation, limited movement range, and fulcrum effect. This highly demanding task, requiring high levels of expertise in laparoscopy, was difficult to master and this ultimately led to longer warm ischemia times and poor graft function [2, 69].

Robotic assistance, however, has helped overcome the difficulties of laparoscopic renal transplantation. Since its first description, it is now becoming more and more accepted and performed. In a meta-analysis published in 2022, it was demonstrated that robot-assisted kidney transplant is safe and feasible, compared to the open approach it is associated with a lower risk of surgical site infection, less postoperative pain, and shorter length of hospital stay, while there is no difference in renal function, graft, and patient survival. It can be especially beneficial for obese patients due to the assessed lower risk of surgical site infections [70]. A notable limitation of the procedure for now is that most centers exclude all patients with calcified iliac arteries from the robotic approach, while chronic renal insufficiency is notoriously associated with atherosclerosis. This limits the use of this technique in more frail patients who would possibly benefit most from a minimally invasive approach.

Calcification of the arteries creates a change for robotic surgery because of the potential disastrous complications of vascular injury or inefficient clamping. In an experiment conducted by Le et al. in 2013, it was proven that robotic bulldog clamps exerted significantly less clamp force compared to laparoscopic clamps [71]. This issue could be potentially overcome by developing more robust robotic vascular clamps.

Robot-assisted lung transplantation

In 2023, as reported by Emerson et al., the first robot-assisted lung transplantation was performed successfully. The robot was used for the removal of the recipient's diseased right lung and after the donor's lung was inserted into the chest, the bronchial and the left atrial anastomosis were created with robotic assistance. The pulmonary artery anastomosis was then performed under direct vision due to the longer ischemic time at that point. The patient recovered without any major adverse events and was discharged on the 11th postoperative day. Since then, several more robot-assisted lung transplants have been performed by the team [72].

Portal vein reconstruction in robot-assisted pancreaticoduodenectomy

Pancreatic cancer is widely recognized as one of the most vicious tumors, with only 5% combined 5-year survival rate. Although surgical therapy is the most effective treatment, a minority of the patients are candidates for it, due to locally invasive disease or the presence of distant metastasis. Pancreaticoduodenectomy (PD) as described by Whipple in 1935 is the gold standard procedure for pancreatic head tumors to this day. It is considered one of the most complex surgeries of the alimentary tract due to the challenge of careful dissection along critical vascular structures and then the restoration of the enteric continuity, requiring three anastomoses (pancreaticojejunostomy, hepaticojejunostomy, and gastrojejunostomy). This demanding operation has high morbidity and mortality rates even at high-volume centers [73]. Like in the case of many previously described areas, laparoscopy could not gain widespread popularity, although it was first described more than 20 years ago [74]. The technically challenging requirement of retroperitoneal dissection in close proximity to major vascular structures and the need to perform the reconstruction with laparoscopic instruments made it difficult to master this procedure. Robot-assisted surgery promises to overcome many boundaries of the traditional minimally invasive approach.

When the tumor involves the superior mesenteric or portal vein, portomesenteric resection is now considered the standard of care. A patient is considered a candidate for robotic PD in case of venous involvement is less than 180° circumferentially and the vein is patent [75, 76]. After resection is complete, reconstruction is required, which is an essentially vascular surgical procedure, performed with robotic assistance. According to the International Study Group of Pancreatic Surgery (ISGP) classification, types of vein resection can be divided into four categories. Type 1 resection means a small side wall resection, which can be closed with direct suture. In case of type 2 resection, patch closure is required. In the case of type 3 and 4 resections, a complete segmental resection is required, which can be reconstructed with direct repair in the former, and only with interposition in the latter. If the resection involves the splenomesenteric junction, the surgeon has to sew in a mini-Y graft with three robot-assisted anastomoses to preserve the flow [76]. This requires high-level vascular surgical skills and can be easily considered a "vascular" operation.

Robotic coronary artery bypass grafting

Although the first reported endoscopic bypass grafting was performed in 1998, by a French group, this approach faced similar criticism as other vascular surgical procedures [77]. These were the lack of haptic feedback, steep learning curve, high costs, lack of standardized training, concerns regarding the conversion rates, difficulties of creating multi-vessel revascularization, and long-term durability [78]. Recently, Balkhy et al. published their experience with totally endoscopic coronary artery bypass (TECAB) in 544 patients. 56% had multi-vessel revascularization and 242 patients underwent hybrid revascularization. Only one patient required conversion with sternotomy due to bleeding and there were six reoperations (1.1%) with four requiring sternotomies. Early mortality was 0.9% and at a median follow-up of 36 months, cardiac-related mortality was 2.4%, with freedom from MACE being 93% [79].

One of the critical points of TECAB is the creation of vascular anastomosis. There have been proprietary devices developed to ease this procedure, including the C-Port Flex A distal anastomosis device, and the PAS-port proximal anastomosis device (Cardica, Redwood, CA, USA). Utilization of such an anastomotic device significantly shortened operation times, but did not significantly affect patency compared to the sutured approach in a large single-center retrospective analysis [80].

Transitioning skills learned and devices developed for cardiac procedures have the potential to advance the adoption of vascular surgical procedures in the realm of robotics.

Training pathway to becoming a vascular robotic surgeon

As previously demonstrated, many "vascular" procedures are constantly being performed, many by other specialties; however, vascular surgery performed with robotic assistance is still considered barred by many. Although these procedures have core vascular surgical elements, the current generation of vascular surgeons receive no training in robotics, which also means they lack the skills to solve occasional vascular complications, without the need for a conversion when called into the OR emergently. That is why setting a training pathway for fellows and vascular surgical residents is of paramount importance. Fellows coming to vascular surgery may have basic training in laparoscopy or even robotic surgery; therefore, their expertise in this field can be built upon.

Our current strategy is to focus on individuals having experience with laparoscopy to train them in robotic surgery through a complex pathway. This includes basic robotic training, simulation on the manufacturer's platform, wet lab practice, and case observations. This is followed by five robotic cases with the supervision of an external proctor. We determined a graduated increase in case complexity, starting from low complexity high-volume cases, such as peritoneal dialysis catheter insertion with lysis of intraabdominal adhesions through gradually more complex cases like venous repairs to highly complex and more demanding operations, like median arcuate ligament release, visceral aneurysm repair, and type 2 endoleak repair after stentgraft placement. This graduality in case complexity along with the increasing volume of cases allows appropriate experience to be gained to handle the more complex procedures. However, neither vascular robotic surgery nor this method has been accepted by the vascular community. We need further discussion and a concurrent position statement on this topic.

Future perspectives of robotic vascular surgery

Future robotic surgical systems could include the following improvements to the current generation of robotic systems. The concept of "master–slave" controls in robotic systems can be reimagined to reflect the levels of surgical autonomy and provide real-time assistance to surgeons with a smart robotic setup and positioning, including a certain level of automation of repetitive surgical tasks [81]. The current concept of streaming a set of imagery (laparoscopic camera, patient hemodynamics, preoperative imaging) and letting the surgeon integrate the relevant procedural stage-specific information could be adapted to a surgical-state intelligence system that provides integrated imaging, sensing, and feedback to the surgeon in the console. This could include better visualization of preoperative and intraoperative 3D imagery using novel image visualization systems [82]. Integration of intraoperative imaging systems for real-time visualization of robotic devices and changes in vascular anatomy can be adopted to improve imaging, visualization, and 'integrated navigation" of future robotic systems [83]. Real-time image processing systems can impact how intraoperative imagery is generated and visualized during surgical procedures. This could include automatic tissue/target organ recognition and delineation of surgical tools/steps and complications using machine-learning algorithms. The major difference between conventional open surgery and robotic-assisted laparoscopic surgery is the lack of tactile sensation. Latest-generation robotic systems have been exploring the added clinical value of providing tactile feedback to the user using sensors and trackers built into the robotic instrument [84]. Automated recognition of surgical gestures, including quantification of surgical performance could be an insightful way of understanding surgical skills, and potentially optimize surgical performance and predict patient outcomes for robotic surgical procedures [85].

Conclusion

In the field of robotic surgery, there has been a dramatic improvement in technology, technique, and adoption of a wide array of specialties. In vascular surgery, the robotic approach is still in its infancy, despite many "vascular procedures" being performed by non-vascular specialists. Although this technique holds the promise of delivering the core therapeutic elements of an open approach through a keyhole incision, it is still to be determined whether the same durability can be achieved. Promising data originating from only a handful of centers worldwide. There is still a huge need for dedicated robotic vascular instruments, namely forceps and aortic clamps to be developed. In addition, dedicated robotic surgery training pathways for vascular surgeons have to be developed and embraced by the vascular community.

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Declarations

Conflict of interest BCL, SC, and CSB have no competing interests. PC is a consultant senior scientist at Occam Labs LLC, Santa Cruz, CA, and interventional consultant at Siemens Medical Solutions, USA Inc., Malvern, PA. ABL received research support from W. L. Gore & Associates, he also consults with Boston Scientific, W. L. Gore & Associates, Siemens, and is a shareholder in Hatch Medical.

Ethical approval The research and review processes comply with the ethical guidelines and principles set forth by relevant professional organizations and institutional review boards. Any studies involving human or animal subjects referenced in this review have followed ethical standards as outlined in the respective original publications.

Informed consent Patients provided informed consent for the publication of anonymized, deidentified, intraoperative images in Figs. 2, 3, and 4.

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