

Robotic general surgery: current practice, evidence, and perspective

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Abstract

Background Robotic technology commenced to be adopted for the field of general surgery in the 1990s. Since then, the da Vinci surgical system (Intuitive Surgical Inc, Sunnyvale, CA, USA) has remained by far the most commonly used system in this domain. The da Vinci surgical system is a master–slave machine that offers three-dimensional vision, articulated instruments with seven degrees of freedom, and additional software features such as motion scaling and tremor filtration. The specific design allows hand–eye alignment with intuitive control of the minimally invasive instruments. As such, robotic surgery appears technologically superior when compared with laparoscopy by overcoming some of the technical limitations that are imposed on the surgeon by the conventional approach.

Purpose This article reviews the current literature and the perspective of robotic general surgery.

Conclusions While robotics has been applied to a wide range of general surgery procedures, its precise role in this field remains a subject of further research. Until now, only limited clinical evidence that could establish the use of robotics as the gold standard for procedures of general surgery has been created. While surgical robotics is still in its infancy with multiple novel systems currently under development and clinical trials in progress, the opportunities for this technology appear endless, and robotics should have a lasting impact to the field of general surgery.

Keywords Robotic surgery · General surgery · da Vinci · Robotics

Introduction

Surgery has traditionally been an arena with a strong surge for improvements to the benefits of many patients. Several milestones in the history of surgery revolutionized the treatment, including the discovery of asepsis, the development of modern anesthesia, and many others including the invention of laparoscopy. While these major quantum leaps appear genius in retrospect, they were often the subject of debate and sometimes even disdain in their time. As such, Kurt Semm, who performed the first laparoscopic appendectomy in Germany in 1981, was at risk to have his medical license revoked for his work in the development of minimally invasive surgery [1, 2]. In the years to follow, laparoscopy was progressively adapted for many general surgery procedures as it became evident that peri-operative patient outcomes could be improved using minimally invasive approaches. As a further progression in advancing minimally invasive surgery beyond manual laparoscopy, early developments of robotic for general surgery commenced in the 1980s with trans-disciplinary collaborations in the Silicon Valley. During that time, the National Aeronautics and Space Administration Ames Research Group developed a head-mounted display which was originally meant to transmit large amount of data from space missions to co-coordinators on the ground [3]. Around the same time, VPL Inc. developed the DataGlove—a wired glove that allowed physical interaction with virtual scenes. The liaison of these two innovators combined with the robotic expertise of the former Stanford Research Institute gave birth to a first robotic system that was suitable for applications in minimally invasive general

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surgery. Further refinements of the system lead to the development of the da Vinci surgical system that was commercialized by Intuitive Surgical Inc. (Sunnyvale, CA, USA). Since the first clinical application in 1998 with a pre-market prototype called Mona, the da Vinci standard system developed over the S and Si system to the latest launched product, the da Vinci Xi (Fig. 1), which was released in 2014 (<http://www.intuitivesurgical.com/products/>) [4]. Over the years, the da Vinci system family has been used for an increasing amount of procedures from many fields of surgery [5–7]. Adoption was mainly driven by the continuous surge to improve clinical outcomes by overcoming technical limitations of conventional laparoscopy as the da Vinci surgical systems dispose of a variety of technical specifications including:

- physical separation between patient and surgeon with computer interface
- true three-dimensional vision with up to ten times magnification
- endo-wristed instruments (Fig. 2) with seven degrees of freedom
- software features including motion scaling and tremor filtration
- strong hand–eye alignment resulting in intuitive control of instrumentation by the surgeon
- computer interface in between the patient and the surgeon



Fig. 1 Robotics arms of the da Vinci Xi system (courtesy of Intuitive Surgical Inc.)



Fig. 2 da Vinci wristed instruments (courtesy of Intuitive Surgical Inc.)

As such, it is evident that the technical specifications far exceed the ones of conventional laparoscopy, and it can be assumed that the robotic system is capable of overcoming some of the limitations of a conventional laparoscopic approach. While laparoscopy has become the gold standard for a variety of rather easy general surgery procedures, the penetration for advanced surgeries of advanced complexity which might either be derived by space constraints or technical demands has been limited [8–10]. Exactly in these surgical spaces, the da Vinci surgical system appears as a potential “enabler” of minimally invasive surgery by overcoming the technical limitations of conventional laparoscopy. As such, while laparoscopic radical prostatectomy is a very challenging and rarely performed procedure, the robotic approach has been established as the gold standard for the removal of prostate cancer [11]. The value of robotics for this procedure has been clearly established by high-level-of-evidence studies, including prospectively randomized trials and high quality meta-analyses [12–14]. As a result, robotics for radical prostatectomy received positive evaluations by several health technology assessments and is the recommended surgical method by clinical guidelines [11].

While the role of robotics for radical prostatectomy appears clear, the application in the field of general surgery is less evident, and it requires careful analysis whether the aspirational value of the doubtless superior technology reliably results in improved patient outcomes ultimately leading to clinical and cost effectiveness. As such, this manuscript aims to review the current practice, evidence, and perspective of robotic general surgery.

Clinical applications of robotics in general surgery

Please refer to Table 1 for a list of prospectively randomized trial of robotic general surgery.

Table 1 Randomized controlled trials comparing robotic surgery to alternative approach

Authors	Procedure	Comparator	No of subjects (robotic/comparator)	Key outcomes
Mueller-Stich et al. [15]	Fundoplication	Laparoscopy	20/20	Robotic with shorter OR time, higher costs. Similar short-term outcome
Draaisma et al. [16]	Fundoplication	Laparoscopy	25/25	Similar outcomes of all parameters
Morino et al. [17]	Fundoplication	Laparoscopy	25/25	Similar outcomes of all clinical parameters. Higher costs for robotics
Nakadi et al. [18]	Fundoplication	Laparoscopy	9/11	Similar outcomes of all clinical parameters, longer OR times, and higher costs for robotics
Sanchez et al. [19]	Gastric Bypass	Laparoscopy	25/25	Shorter OR times for robotics during learning curve, decrease maximized with larger BMIs
Ruurda et al. [20]	Cholecystectomy	Laparoscopy	10/10	Longer setup times for robotics
Heemskerk et al. [21]	Cholecystectomy	Laparoscopy	11/11	Less physical stress and mental strain for the surgeon with robotics
Baik et al. [22]	Tumor specific mesorectalexision	Laparoscopy	18/18	Longer length of stay for robotics
Jimenez et al. [23]	Total or subtotal mesorectal excision	Laparoscopy	28/28	Greater distal margins, longer setup time, longer OR time for robotics
Park et al. [24]	Right colectomies	Laparoscopy	35/35	Longer OR time, higher costs for robotics
Patriti et al. [25]	Total mesorectal excision	Laparoscopy	29/37	Shorter OR time, fewer conversions
Somashekar et al. [26]	Rectal resection with total mesorectal excision	Open Surgery	25/25	Greater distal margins, lower estimated blood loss, shorter length of stay, longer OR time for robotics

Foregut surgery

Robotic fundoplication has been adopted as an early application of da Vinci in general surgery, and a variety of publications demonstrate the safety and general feasibility of the robotic version of this procedure [27, 28]. Four randomized controlled trials of limited quality comparing robotic to laparoscopic Nissen fundoplication can be found in the up-to-date literature [15–18]. While all of these RTCs showed similar short-term clinical outcomes, one publication reported shorter operating room (OR) times for robotics [15] and another observed longer OR times [18]. Three RTCs demonstrated higher costs for the robotic procedure when compared to laparoscopy [15, 17, 18]. As such, several meta-analyses using different literature as the basis for calculations conclude that robotic Nissen fundoplication results in similar clinical outcomes when compared to the laparoscopic procedure [29–31], but OR times are longer [29] and costs are higher [29, 31].

While no RTCs that evaluates robotic Heller myotomy can be found, several comparison studies showed a perforation rate of 0 % for the robotic patients with otherwise comparable clinical outcomes [32–34]. One study observed higher quality of life after robotic Heller myotomy when compared to conventional laparoscopy [33]. As such, a meta-analysis by Maeso et al. concluded that robotic Heller myotomy appears to result in fewer perforations and higher postoperative quality of life when compared to laparoscopy [30].

Several reports can be found in the robotic application for early gastric cancer with similar indications as for a laparoscopic approach. While no RTCs exist comparing robotic gastrectomy with alternative methods, several meta-analyses using lower-level-of-evidence comparative studies analyze the value of robotics for gastrectomy [35–40]. Overall data suggest that robotic surgery for gastric cancer is safe and feasible and results in similar peri-operative outcomes when compared to conventional laparoscopy. It appears that operative time might be prolonged when using robotic technology [35, 36, 38], but there might be an advantage in regards to length of stay and estimated blood loss for robotic gastrectomy [35, 36, 38–40]. In addition, it has been suggested that the technical specifications of robotic technology enable a minimally invasive approach to D-2 lymphadenectomy [41]. This procedure has been established as the gold standard of treatment, with improved long-term oncological outcomes for the patients when compared to a limited D-1 lymphadenectomy [42]. Overall, more systematic data are needed to verify this potentially very meaningful advantage of robotics over conventional laparoscopy.

Bariatric surgery

While bariatric surgery is currently predominantly performed by conventional laparoscopy, several distinct anatomical challenges often exist, including a thick abdominal wall,

hepatomegaly, and increased amounts of intra-abdominal fat. As such, procedures are usually challenged by a limited workspace, reduced surgical dexterity, and limited dexterity during conventional laparoscopy. Literature from other fields of surgery indicates that robotics may facilitate surgery in the obese population [43, 44], and thus robotics might be of relevance in the field of bariatric surgery.

The largest volume of clinical publications on robotic use for bariatric indications can be found for Roux-en-Y gastric bypass (RYGB). Since early reports in 2003, multiple groups have published their clinical outcomes with a variety of surgical methods, including hybrid and total robotic approaches to RYGB. While some of the early articles reported challenges of the robotic technology, mainly around the absence of force feedback leading to bowel injuries [45], more recent comparative studies [46–48] as well as systematic reviews [49, 50] do offer some evidence supporting the potential clinical advantages of robotic RYGB surgery, particularly in regards to the quality of the gastro-jejunal anastomosis. As such, a meta-analysis by Markar et al. showed lower rates of gastro-jejunal stricture with the robotic approach when compared to the laparoscopic approach [50]. This reduced stricture rate as well as potentially reduced rates of gastro-jejunal leaks [46, 51, 52] can be explained by the different technique that is usually used for the formation of gastro-jejunal anastomosis during robotic gastric bypass: while most gastrojejunal anastomoses during conventional laparoscopy are formed by either a circular or a linear stapler, robotic technology enables a “hand-sutured” anastomosis which might result in enhanced clinical outcomes. In addition, the only RTC from the field of robotic bariatric surgery showed significantly shorter OR times for robotic gastric bypass during the surgeon’s learning curve when compared to conventional laparoscopy [19].

While some clinical evidence exists for robotic gastric bypass, much less is evident for other bariatric procedures. Potential reasons might include the fact that some alternative procedures such as gastric sleeve resection and gastric banding are less challenging, and thus conventional laparoscopy is more feasible or that other procedures such as duodenal switch with bilipancreatic diversion is a relatively rare indication.

In that context, the value of a robotic approach to sleeve gastrectomy (SG) appears unclear at present; although the robotic approach may facilitate the mobilization of the stomach and enable suturing of the previously stapled tissue, the most critical element of this procedure remains the formation of the gastric sleeve using staplers. Although robotic staplers for the da Vinci system have recently been released in limited geographies, no systematic data can be found for their application of gastric sleeve resections so far. Further experience with the robotic staplers will show whether this procedure might gain significance as a robotic approach. To date, literature consisting only low-level-of-evidence studies indicates

general feasibility and safety with potentially prolonged operative times [53, 54]. One research group analyzed their series of robotic-assisted SGs and compared data to a systematic review of laparoscopic sleeve gastrectomies (LSG). This analysis showed lower leak and stricture rates with the robotic approach to SG [55].

Similarly, the clinical evidence for robotic installation of adjustable gastric band (AGB) is limited as few low-level-of-evidence studies can be found. Since the first report of a robotic placement of an AGB by Cadiere and Himpens in 1998 [4], other authors have reported on the feasibility and safety of performing robotic AGB placement [56, 57]. Although it seems apparent that robotic technology might provide advantages during some parts of the dissection and suturing the anterior gastric plication, the lack of tactile feedback may be a disadvantage during the preparation of the posterior gastric tunnel. However, the most significant barrier for robotics for this indication might be the limited technical challenge that is posed. Thus, robotics might only provide limited incremental value over conventional laparoscopy with at least currently increased costs.

Finally, biliopancreatic diversion with duodenal switch (BPD/DS) and revisional surgery (RS) have been reported to be feasible using the da Vinci surgical system [58–60]. While both procedures are of advanced complexity where robotics might potentially impact clinical outcomes positively, a very limited number of low-level-of-evidence studies can be found in the literature. Due to its limited application and the extensive need for multi-quadrant access, BPD/DS will most likely not develop into a dominating robotic indication with the currently existing robotic systems. However, revisional surgery is currently significantly increasing in terms of case numbers in the first world, and some reports can be found in the literature [59, 60]. In addition, with the complexity of these procedures, a robotic approach appears to be a suitable option. As such, it can be estimated that the body of evidence in regards to robotic RS will increase over the next few years to allow a definite statement in the future.

Hepatobiliary and transplant surgery

With some evaluations of case-matched or randomized design comparing robotic multiport cholecystectomy with conventional laparoscopy showing similar clinical outcomes with increased costs and longer setup times for robotics, the routine clinical application of robotics for simple cholecystectomy appears limited [20, 61]. Still recently, it seems that the technique of multiport robotic cholecystectomy has been used in increasing numbers, and some reports that describe cholecystectomy as a procedure suitable to train residents on the da Vinci surgical system or for cases of advanced difficulty can be found [62–65]. A recent RTC has also showed that physical stress and mental strain might be reduced for the surgeon

when cholecystectomy is performed using the da Vinci system in comparison to conventional laparoscopy [21]. More data in regards to single-site cholecystectomy are described below.

A number of reports from the field of robotic liver and pancreas surgery can be found; however, all studies are of limited quality at this point. So far, literature suggests the general feasibility of robotics for all common pancreatic resections including distal, central, and total pancreatectomy as well as for pancreaticoduodenectomy. Some potential short-term advantages over open surgery and conventional laparoscopy might be confirmable with more systematic research in the future [66, 67]. Similarly, robotic liver resections have been reported to be safe and feasible when performed by experienced groups [68, 69]. Overall, robotics appear promising in this field of advanced general surgery as this technology seems to have advantages that facilitate a variety of surgical maneuvers that are needed during liver resection. Still, more advanced robotic instrumentation will be needed to enable widespread application in the field of liver surgery.

While the robotic approach to donor nephrectomy has been described since the early years of robotics in general surgery [70–72], more advanced procedures from the field of robotic transplant surgery have only emerged in more recent years as a sign of progressive penetration of robotics into advanced areas of general surgery [73]. Described procedures include those on kidney, pancreas, and combined transplantations [74–77]. However, besides feasibility in very experienced hands, no firm evidenced-based conclusions can be drawn at this rather early point in the adoption curve.

Colorectal surgery

A good number of publications—mostly with limited quality though—can be found for robotic application in colorectal surgery, and general feasibility of robotics in colon surgery can be assumed [78, 79]. While the technical advantages of robotics could play a role during more complex maneuvers, including extended lymphadenectomy and the formation of intra-corporeal anastomoses [80–82], more substantial clinical evidence is needed to clearly define the role of robotic technology for colon surgery. So far, a single RTC in regards to right colectomy showed longer OR times and higher costs for the robotic technique [24].

A greater body of evidence can be found for the application of robotics in rectal surgery, particularly regarding the treatment of rectal cancer. A RTC of robotic rectal resection versus open surgery has shown greater distal margins and significantly lower blood loss with the robotic technique [26]. Conventional laparoscopy has been described as a safe and effective alternative to the open approach, but relatively high rates of conversions and circumferential margin positivity have been the results of systematic research [83–85]. Therefore, the laparoscopic approach has not yet been

established as the gold standard approach for patients with rectal cancer [9, 86]. The technical superiority of robotics holds the promise to overcome the limitations of conventional laparoscopy in this setting and may result in fewer conversions and reduced rates of positive margins when compared to conventional laparoscopy [22, 87–90]. Some RTCs from this field also showed greater distal resection margins, fewer conversions, lower estimated blood loss, shorter length of stay, either shorter or longer OR times, and longer setup time for the robotic technique [23, 25, 91]. However, despite the fact that these studies are of randomized control design, the number of subjects is limited, and long-term outcomes are outstanding. Therefore, more systematic research of the field of robotics for rectal cancer is currently underway and first results are expected in the near future [87].

As a relatively novel and highly interesting procedure, robotic transanal resection of low-risk rectal cancers and benign conditions has recently been developed. Several research groups have published their laboratory experience as well as initial clinical experience of transanal robotic surgery (Fig. 3) for local excisions and retrograde total mesorectal excision [92, 93].

Special da Vinci platforms

Earliest reports of robotic single-site surgery (Fig. 4) encompass experiences with robotic surgery using multiport da Vinci instruments docked through a single incision with robotic instruments placed in unconventional arrangements [94]. Later, a dedicated set of semi-rigid instruments and curved cannulae for robotic single-site surgery was released in 2011 [95]. This platform was pre-dominantly used for cholecystectomy. Literature shows the general safety and feasibility of the technique with potentially shorter OR times and facilitated learning curves when compared to conventional single-incision laparoscopy [96, 97]. Several reports can be found on the application of robotic single-site surgery for other procedures [98]. Recently, an articulated needle holder was developed for the use with the robotic single-site platform to facilitate



Fig. 3 da Vinci transanal surgery



Fig. 4 da Vinci single-site cholecystectomy

suturing, but literature is still outstanding in regards to its potentially clinical value.

Another addition to the da Vinci Si technology has been the development of an intra-operative near-infrared fluorescence imaging system. This technology has been used during a variety of surgical procedures to visualize blood flow (Fig. 5), lymph node mapping, and intra-operative cholangiography and to identify the anatomy of the surgical field [99–101]. Systematic research will be needed to determine the impact of this technology on clinical outcomes.

Summary of literature review

Reflecting upon this literature review of robotics for general surgery, it becomes obvious that there is a serious lack of evidence for the clinical value of robotics in general surgery: a limited number of studies are of the highest level of evidence, but often of limited quality. Shortcomings include small patient cohorts, room for various sources of bias, and lack of long-term outcomes. As such, meta-analyses are also of limited robustness, and it remains unclear if the undisputed technical advantages of the da Vinci surgical system over conventional laparoscopy result in a clinical advance for the patient. Several reasons are worth discussing in that context: first, robotics is still at its infancy at the current point in time.

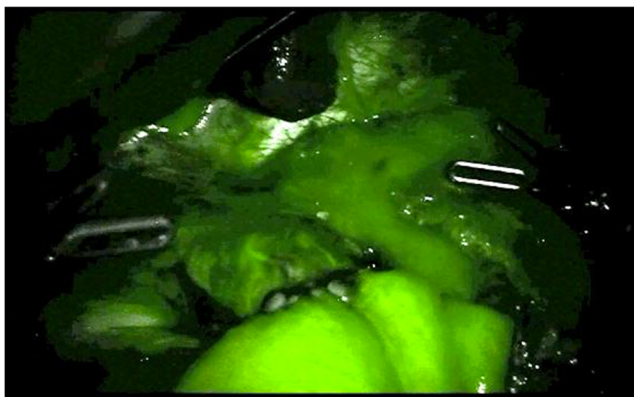


Fig. 5 da Vinci fluorescence imaging of gastric pouch during gastric bypass

It has been less than two decades since the first robotic general surgery procedure was performed. As such, many potentially very interesting indications of robotics in advanced general surgery—mainly where laparoscopy is not applicable due to its technical challenges—have not fully been explored yet. Creating significant clinical evidence takes time and a natural “publication curve” from lowest level of evidence studies such as case reports to high-quality randomized trials, and meta-analyses have to be taken into consideration. While lower level of evidence research clearly indicates a potential clinical value of the robotic technology, there are serious barriers for the conduct of randomized controlled trial including organizational challenges and costs. At the present point in time, the robotic market appears to be not yet saturated as procedure numbers are rising despite this lack of clear clinical evidence. As such, there does not seem to be enough “pressure” for delivering concrete data in regards to clinical and cost effectiveness of robotic technology. However, besides academic interest, global challenges in the health market including increasing economic challenges will drive further research in the field of robotics for general surgery. Thus, several high-quality trials comparing robotic technology to either open or laparoscopic surgery are on their way, and their results are awaited with great anticipation [87, 102].

Perspective of robotic general surgery

Despite the currently limited proof of the clinical and cost effectiveness of robotics for general surgery, the robotic technology clearly holds the promise of revolutionizing conventional general surgery—ultimately for the benefit of many patients to come.

On one hand, the currently most commonly used da Vinci surgical system is subject to constant improvements including the recent release of a novel version that promises to facilitate multi-quadrant surgery, the addition of new instruments, and the augmentation of functions by integration of novel technologies such as enhanced vision and many others. While many new technologies are also developed for open and laparoscopic surgery, the possibility of seamless integration into one surgical tool is only possible when a computer is the central element of surgical care—such as a robot. In addition, a variety of other robotic surgical systems are being developed at present and brought to clinical applications in the near future.

Some are console–cart systems with an operator seated at a console and instrument carts, which will create direct competition for the da Vinci. These systems share many of the essential features of the da Vinci surgical system and may be subject to intellectual disputes such as previous systems before potentially entering the market. For all of these systems, the surgeon works at a control console, observes video feeds of the operating field, and remotely controls end-effectors that

are installed in or around the patient who is placed in a sterile field in the operating room. A common challenge of console–cart systems appears to be the setup process that is required for the correct installation and the costs for the hardware and software as well as for the reusable instrumentation. On the other hand, these systems are most capable to deliver intuitive control, as well as the capability to enable tele-surgery and tele-mentoring.

While none of such console–cart systems besides the da Vinci surgical system has yet been released for widespread commercial distribution, several products are anticipated to be available soon. Each of them offers distinct features that promise to improve the existing technology and thus hopes to conquer a piece of the surgical market by providing superior patient outcomes and/or reduced costs.

A frequent criticism about the da Vinci system is the absence of tactile feedback for the surgeon, which can lead to unexpected strain on tissue and inadvertent injuries. This lack has created an avenue for new development: The University of Pennsylvania is currently developing a product called “Verro Touch” which will be capable to add haptic capabilities to the da Vinci surgical system by providing tactile and auditory feedback to a da Vinci operator based on instrument vibration [103].

The Telelap ALF-X system is a novel telesurgical system developed by SOFAR s.p.a. in. Its design consists of a four-arm system with innovative tactile sensing capabilities. The company claims to streamline the robotic surgical experience by improving safety, providing natural perception, ease of use, and cost effectiveness (ALF-X T. www.walf-x.com).

The DLR MIRO is a modular system of robotic arms being developed by the Institute of Robotics and Mechatronics in Germany. The MIRO is a multi-jointed surgical arm that can be used alone or in groups to perform a wide variety of surgical tasks. Thus, a single MIRO might be used in conjunction with a human surgeon to perform specific visualization or manipulation tasks (DLR, <http://www.dlrde/rmc/rm-neu/en/desktopdefault.aspx/tabid-3828/>).

Titan Medical Inc. in Canada is developing the SPORT™ (Single Port Orifice Robotic Technology), which is a system for use in minimally invasive surgery. The SPORT™ is a single-port robotic platform that includes a 3-D vision system, articulated instruments, and a surgeon workstation. Similarly to the da Vinci surgical system, it offers an interface to the robotic platform for controlling the instruments and providing a 3D endoscopic view of the surgical field. The company aims to expand the use of robotics to currently underserved surgical areas, and commercialization is currently expected for 2017 (Inc. TM. www.titanmedicalinc.com).

Besides these emerging console–cart systems, direct image-guided robots might be of relevance for the field of general surgery in the future. In these kinds of systems, the movements are not directly controlled by a surgeon, but rather directly by a computer to precisely fit certain constraints

determined by imaging. Therefore, these systems are not considered master–slave systems and might be closer to the natural perception of a “robot” than currently available systems for general surgery. Considering the complexity of soft tissue surgery, these systems are mainly for relatively simple and very specific surgical subtasks during which close tolerance is desirable and can also be considered as “smart power tools”.

Examples of such systems include the Cyberknife which was approved by the FDA for human use in 2001 for delivering precision dosages of radiation to tissue. Using imaging data, the Cyberknife radiates a specific site from multiple angles, which reduces the effect on the surrounding tissue while maximizing dosage in the desired area. Since its introduction to the market, the Cyberknife has been used on a wide variety of tumors in locations throughout the body [104–106]. Other direct image-guided robots include the SpineAssist by Mazor Robotics and the Robotic Arm Interactive Orthopedic System (RIO) by MAKO Surgical Corp; both systems currently target orthopedic procedures as soft tissue deformation remains a serious constraint for the use of these kinds of robots for the field of general surgery. Recent developments of novel direct image-guided robots that might be applicable to procedures of general surgery are aimed to use magnetic resonance imaging to guide access to specific regions. However, no such robotic systems have been approved to date.

In addition, miniaturized surgical robots are being developed as a true quantum leap in surgical technology in the future. These systems are designed as small autonomous or remotely controlled robots capable of operating within the patient’s body. These kinds of robots would be of particular use in constraint spaces with challenging accesses. The currently available PillCam series from Given Imaging, which is mainly used as an alternative to conventional endoscopy, is subject of such research and technological advance that it promises to soon have the possibility of external control. With this capability, a more active interventional role is possible if other miniaturized systems like electrocautery tips, biopsy forceps, or pharmaceutical dispensers are included in the design. Various other miniaturized robotic systems under development include the Heartlander by the Robotics Institute of Carnegie Mellon University, which uses an inchworm-like locomotion system to gently move around on the epicardia, and a microrobot by the Hanyang University in Seoul that crawls inside blood vessels to address occlusive disease. Despite the fact that these systems are still early in their development, it appears evident that the field of robotics offers unlimited opportunities for the future.

Conclusion

Besides the current absence of significant clinical evidence of robotics in general surgery, it seems obvious that robotics hold

the promise to continuously revolutionize the field of general surgery. While clinical evidence will continue to evolve with time, currently available systems are being subject to constant improvement and augmentation with additional technology that is essentially only enabled by having a computer as the central element of surgical care. In addition, new systems are under development, and their commercialization will further shape the landscape of surgical robotics.

Conflicts of interest Monika Hagen is a part-time employee of Intuitive Surgical Inc.

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