REVIEW

Gastrointestinal robotic surgery: challenges and developments

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Abstract: The rapid diffusion of new technologies in surgery, together with high expectations of both patients and the mass media, has led to many gastrointestinal procedures being approached using robots. Robotic technology seems to resolve many of the drawbacks of laparoscopic advanced procedures, such as anastomotic reconstructions, accurate lymphadenectomy, and vascular sutures. In addition, a deeper tridimensional steady vision with excellent high definition, the EndoWrist technology offering seven degrees of freedom, tremor filtration, scaled motion, optimal working ergonomics, and avoidance of the 'fulcrum effect', are the main strengths of the da Vinci® system. The use of near-infrared technology and the possibility of tutoring through a double-console will most likely add many more advantages of this technology over laparoscopy alone. However, none of the gastrointestinal robotic interventions has reached a level of evidence-based efficacy that enables it to be routinely applied. The main limitations of robotic gastrointestinal procedures are represented by the learning curve, the higher costs of robotic surgery compared to traditional and laparoscopic surgery, and the longer operation times, including setup and organizational troubles. Moreover, while the limits of robotics for benign diseases are mainly represented by technical issues, oncologic outcomes remain the foundation of any procedures to cure malignancies, and long-term follow-up is still lacking. On the other hand, a word of caution should be presented on the adoption of robotics in too many surgical units without the correct and formal technical background and third-party control to guarantee the best outcomes for patients at minimum risk. Therefore, the robotic treatment of gastrointestinal diseases requires a thorough analysis of the published evidence, in order to determine the correct indications and patient selection. This review aims to examine the evidence for the use of robotic surgery in both malignancies and benign disease arising from the gastrointestinal area. Future developments in robotics and ongoing areas of research are also analyzed.

Keywords: gastrointestinal surgery, mini-invasive surgery, da Vinci

Introduction

Gastrointestinal surgery represents a large field for the application of mini-invasive technologies, and gastrointestinal surgeons have contributed, to a large degree, to the widespread adoption of laparoscopy among almost all the hospitals worldwide. Conversely, the merit of the penetration of robotic surgery (RS) in the surgical community is mainly attributable to urologists.[1] In the last few years, there has been widespread adoption of robotic prostatectomy, particularly among high-volume surgeons, which has been associated with a centralization of care and increased economic burden for prostate cancer surgery.[2]

The da Vinci Robot system has been approved for clinical use in the US since 2000.[3] However, as of 2009, according to a large database, very few gastrointestinal

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procedures have been approached in this way, even though early studies have reported better results in terms of the reduction of hospital stay and perioperative deaths compared to open surgery (less than laparoscopy).[4] The following three main barriers to the adoption of robotics for both user and nonuser surgeons have been found to be perceived: low ease of use, usefulness, and control according to a structured questionnaire.[5]

The reasons for this delay could have several explanations. Firstly, the wider gastrointestinal spectrum of procedures with many reconstructive steps has led to challenging learning curves with peculiar anesthetic implications.[6] Moreover, when applying criteria of Health Technology Assessment (HTA), RS has been shown to have higher costs related to the purchase and maintenance of technology and longer operating room time compared to the other approaches.[7] Lastly, the optimum level that has been achieved for some pure laparoscopic gastrointestinal techniques has caused much resistance to the development of a newer complex technology.

Apart from the well-known intrinsic difficulties of surgical research, all these issues could also explain why none of the gastrointestinal robotic interventions have reached a level of evidence-based efficacy that enables it to be routinely applied.[8] Nevertheless, the progressive popularity of RS among urologists, gynecologists, and patients, mixed with some industrial pressure, has led to the worldwide diffusion of the robot in many hospitals.[9,10]

Interestingly, the pioneers[11,12] of general and gastrointestinal RS reported many benefits and few complications of this technique in terms of intraoperative morbidity, return to normal activities and, mainly, feasibility of some of the most complex procedures that were previously precluded by pure laparoscopy without the robotic interface. Moreover, when considering the overall costs in high-volume centers, including reduction of complications and length of stay (LOS), many robotic procedures could become cost-effective except for very simple routine operations, such as cholecystectomy and esophagogastric junction functional surgery.[13,14]

Nevertheless, many of the initial experiences were anecdotal and performed by only a few experienced surgeons, while most of the results were hardly applied out of each single experience.[11,15]

The main advantages of the robotic system are represented by better ergonomic surgeon position, deeper high-definition 3D vision, EndoWrist arm technology (articulation of the instruments with seven degrees of freedom), motion scaling, and tremor filtration. Other additional applications of robotics are the use of near-infrared technol-

ogy (so-called Firefly) and the possibility of tutoring through a double-console,[16] while many others have shown its utility in prospective applications (picture-in-picture preoperative and intraoperative imaging, haptic feedback, EndoWrist harmonic scalpel) (Figure 1).[17]

Interestingly, some concurrent companies, in addition to the only market competitor (Intuitive Surgical, Inc.), have been developing alternative robotic systems, which could lead to some cost reduction.
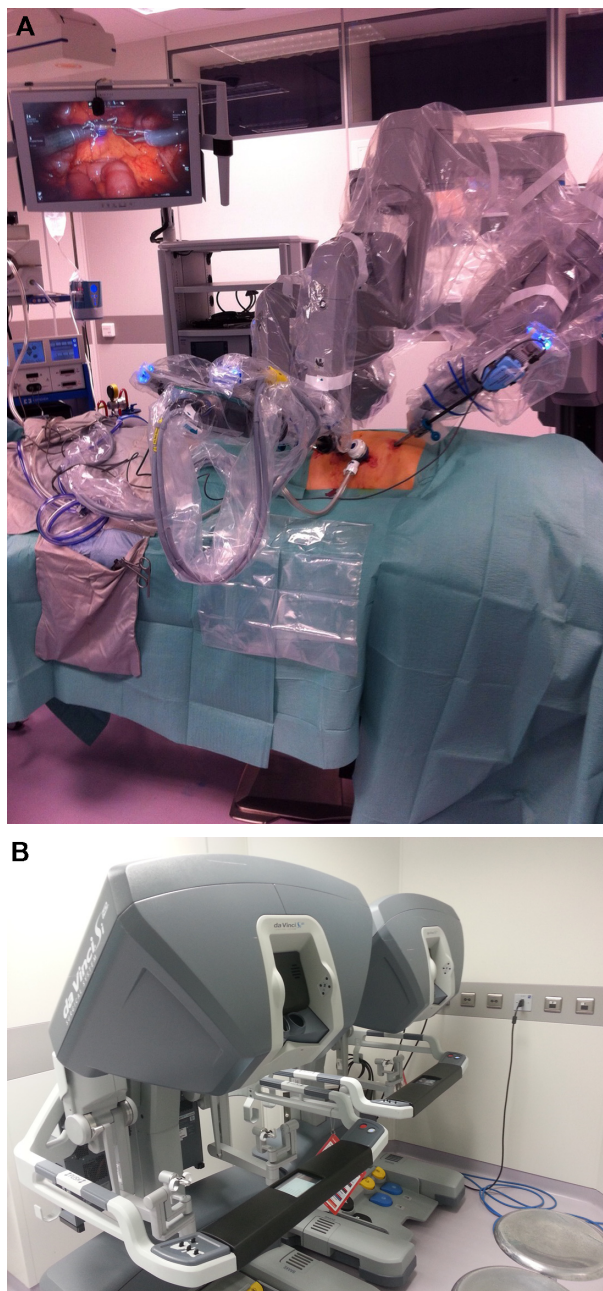

Figure 1 The setting of the da Vinci robotic system (**A**) during a right colon resection at the Careggi University Hospital; and the surgeon console (**B**).

However, if the limits of the widespread adoption of RS are mainly represented by technical issues, learning curves, and costs, oncologic outcomes remain the foundation of most of the gastrointestinal procedures.[18] Any mini-invasive operation, whether laparoscopically or robotically performed, should follow the same oncologic principles of open surgery, generally limiting the skills gain to high-volume centers with subspecialized teams.[19] Furthermore, from an ethical point of view, the application of a full robotic program should follow a few important principles for safety and nonmaleficence, in order to guarantee the maximum safety of each patient during the gaining learning curve.[20]

We focused this review on the full robotic (and some hybrid techniques) treatment of gastrointestinal diseases, including those arising from the esophagus, stomach, liver and biliary system, pancreas, and colorectum, as well as some other miscellaneous techniques (ie, bariatric surgery). If not otherwise specified, the robotic equipment was the da Vinci System® (Intuitive Surgical, Inc.).

A search of the PubMed, EMBASE, and Cochrane databases was conducted until September 2014, including important cross-matched manual references. Randomized controlled clinical trials (RCTs) or meta-analyses were considered a priority. Data arising from English-written, multicentric, international studies, and those with long-term follow-up and oncologic results were also considered of utmost interest, rather than the feasibility of one procedure itself or short-term outcomes.

Esophagus

The minimally invasive surgery of benign and malignant pathology of the esophagus and gastroesophageal junction remains a challenge, although the development and distribution of the robotic platform has allowed an enhancement and improvement of the traditional surgical practice.

A few rigorous articles have been published on the robotic approach to benign disease of the esophagus, and most compared it with open or laparoscopic technique. However, the recent introduction of pure endoscopic techniques and well-established efficacy of medical therapy should lead to a theoretical five arms of study (medical vs endoscopic vs open surgery vs laparoscopy vs robotics), although such studies are very hard to design and to conduct.[8]

All the esophageal procedures for benign disease were codified with a robotic approach, including those for achalasia, reflux disease, and diverticula.[21]

A very large retrospective study by Shaligram et al[22] on 2,683 patients with achalasia, 419 of which underwent

Heller myotomy by open surgery (OM), 2,116 underwent laparoscopic approach (LM), and 149 underwent robotic approach (RM) surgery. No differences in mortality, morbidity, intensive care unit (ICU) admission, LOS, or 30-day readmission were recorded in the groups, but the hospital costs were significantly lower for the LM group (US$7,441±7,897 vs US$9,415±5,515; P=0.0028). A comparison between the OM and RM groups demonstrated significantly lower morbidity (9.08% vs 4.02%; P=0.02), ICU admission rate (14.01% vs 3.36%; P=0.0002), and LOS (4.42±5.25 days vs 2.42±2.69 days; P=0.0001) in the RM group. The authors concluded that the perioperative outcomes were superior in the LM and RM groups when compared with OM. Interestingly, the robotic group also had a slight improvement in perioperative outcomes, though this occurred with the price of some increased costs. Moreover, a recent, very comprehensive review[23] of LM vs RM, including six RCTs (of poor quality) showed similar outcomes for the two methods, and an increased cost for the robotic technique.

Classic laparoscopic fundoplication (LF) has been recognized as the gold standard for surgical treatments of gastroesophageal reflux disease, although a debate still exists on the extent of stomach wrap, specifically, total (Nissen) or partial (Toupet).

Using an American national database, Owen et al[24] analyzed a total of 12,079 patients who received fundoplication procedures with the open technique (OF), LF, and robot-assisted fundoplication (RLF). No differences in mortality, morbidity, LOS, and ICU cases were detectable. RLF resulted in significantly improved morbidity (5.6% vs 11%; P<0.05), LOS (6.1±7.2 days vs 3.0±3.5 days; P<0.05), less ICU admission (11.5% vs 23.1%; P<0.05), and interestingly less cost (US$10,644±6,041 vs US$12,766±13,982; P<0.05) compared to OF, although LF remained superior to RLF, having lower 30-day readmission rate (1.8% vs 3.6%; P<0.05) and cost (US$7,968±6,969 vs US$10,644±6,041; P<0.05).

The conclusions were that RLF had similar patient outcomes to LF, with extra costs and higher readmission rate. This may have been due to the retrospective nature of the study, in which the ongoing learning curve for the more recent introduction of robotics could have played a role in justifying the poorer readmission rate.

A meta-analysis[25] of 221 patients extrapolated by six RCTs, of which 111 underwent LF and 110 underwent RLF, found similar results, with RLF resulting in prolonged total time of surgery, higher costs, and comparable clinical outcomes.

The gold standard of surgical treatment of esophageal carcinoma is partial or total esophagectomy associated with regional lymphadenectomy, but traditional approaches (three-field McKeown procedure with cervical anastomosis, two-field transthoracic Ivor-Lewis resection and the transhiatal esophagectomy – Orringer procedure) have a high incidence of complication, ranging up to 60% and comprising mostly of pulmonary complications, leading to increased LOS, costs, and mortality.[26,27]

The minimally invasive esophagectomy (MIE) technique was designed to reduce surgical trauma, resulting in lower mortality and morbidity rates, and all the above mentioned operations are feasible by laparoscopy (thoracoscopy) or hybrid (some step achieved by open matter) techniques, with excellent results.[28–30] However, MIE is very far from being accepted for routine clinical use worldwide due to the steep learning curve and the unproven cost-effectiveness.[31] Moreover, several technical variables (laparoscopy, thoracoscopy, combined steps, prone or supine position, stapled or hand-sewn anastomosis), together with the general poor quality of the published studies, has contributed to the confounded outcomes and oncologic results.[32]

Robot-assisted, minimally invasive esophagectomy (RAMIE) facilitates esophageal dissection with enhanced visualization of the three-dimensional fields, allowing the execution of complex maneuvers through the articulated instruments, including lymphadenectomy and visceral anastomoses.[33]

The first cases of RAMIE were described by Giulianotti et al,[11] Kernstine et al,[34] and Bodner et al[35] in the early 1920s, but many other surgical approaches have been developed since then.

In 2009, Boone et al[36] reported good postoperative data in 47 robotic three-field esophagectomy (mortality 6%, pulmonary morbidity 44%) and oncologically acceptable results demonstrating its feasibility and safety, with comparable outcomes with the open approach. In 2012, Weksler et al[37] compared the robotic transthoracic procedure with the thoracoscopic approach, and demonstrated the equivalence of the postoperative and oncological data. In 2011, Puntambekar et al[38] reported the technical aspects and postoperative data on a series of 32 patients who underwent robotic-assisted esophagectomy with intrathoracic dissection and lymphadenectomy in the prone position. This group demonstrated an incidence of anastomotic leakage (3/32) comparable to the traditional technique, but a lower incidence of pulmonary complications (2/32), which was related to the benefits of the prone position.

However, the recent trend was directed towards a reduction of the three-field McKeown esophagectomy with cervical anastomosis in favor of the two-field Ivor-Lewis esophagectomy due to a high incidence of leaks, recurrent laryngeal nerve injuries, alteration of swallowing, and pharyngeal transit.[30,39]

The robot-assisted Ivor-Lewis esophagectomy (RA-IL) technique was developed later than the three-field approach, and has greater complexity for construction of the chest anastomosis and is mainly performed with a staple device.[40,41] In a series of 50 patients who underwent RA-IL, de la Fuente et al[42] found a postoperative complication rate of 28% (15/50), including one anastomotic leak (2%), a conduit staple line leak in one patient (2%), and chyle leak in two patients (4%). In all cases, they achieved complete resection (R0) and a median number of lymph nodes retrieved of 18.5.

During MIE, chest esophagogastric anastomosis is performed more frequently with staple devices due to the intrinsic difficulty of performing the procedure, which requires a hand-sewn, video-assisted thoracoscopic suture. However, the articulated instrumentation of the robotic platform can allow these maneuvers with favorable results. Only two papers[43,44] have reported the feasibility and safety of RAMIE with hand-sewn intrathoracic anastomosis. However, these authors had good postoperative outcomes, without a significant prolonging of the operative time, and no increase of leakage, stenosis, and oncologic failures.

Transhiatal esophagectomy was also carried out robotically, with somewhat higher complications, including 35% of patients with temporary laryngeal nerve paresis and 25% of patients with self-limiting cervical leaks.[45]

At present, only very few studies comparing MIE have been published, and none of them have demonstrated real advantages of one method over another.[46,47] A monocentric well-designed trial targeted to robotic MIE started recently.[48] In one study, the learning curve for RAMIE was found to be at least 20 procedures,[49] and very few centers have sufficient case-load to gain adequate specific proficiency, considering how technically demanding this type of surgery is, even in the traditional open way.

Stomach

The recognized standard of care for advanced gastric cancer is complete resection (open gastrectomy [OG]) with at least a formal D2-lymphadenectomy, although a debate on the extent of lymphadenectomy has been ongoing for decades. Some less invasive surgery techniques, such as endoscopic

submucosal dissection and sentinel node mapping, could be appropriate for selected patients with T1 cancers.[31]

Despite the advancements in recent years in laparoscopy (ie, colorectal surgery), the keyhole approach to gastric surgery is still debated and exclusive to a few skilled surgeons, many of them working in Eastern countries.[19,31,50] The limits for the widespread use of laparoscopic gastrectomy (LG) are represented mainly by the technical difficulties in both anastomosis, lymphadectomy and conflicting benefits. Nevertheless, two very comprehensive meta-analyses concluded that LG is better or comparable to open surgery with regards to early and long-term outcomes, although at the price of a longer duration of surgery.[51,52] One rigorous RCT (KLASS trial) confirmed equivalent early outcomes of laparoscopic and open approach to gastrectomy for cancer.[53]

RS for gastric cancer has been demonstrated to overcome intrinsic limitations of conventional laparoscopic surgery, thanks to the wristed instruments that allow seven degrees of freedom, tremor filtering, three-dimensional vision, and a steady image, thus minimizing blood losses and surgical trauma and improving the surgeon's dexterity when fine manipulation is required. This can be especially helpful during maneuvers in restricted fields and around major vessels, such as in extended lymphadenectomy.[54,55] Many of these issues could explain the shorter learning curve of robotic gastric surgery compared to laparoscopy.[56,57]

The first experiences of robot-assisted gastrectomy (RAG) were published almost 10 years ago,[11,58] and more recent papers reported no appreciable differences between patients who had RAG and LG in terms of surgical complications, mortality, conversion rate, LOS, and oncological adequacy.[59,60] However, only very few meticulous studies have been published on RAG, and a recent meta-analysis[61] selected only three RCTs comparing robotic surgery and laparoscopy. No significant differences in terms of complications, mortality, conversion, LOS, and number of nodes retrieved were detected between the two groups. A more inclusive meta-analysis[62] reached the same conclusions, with some trends of better perioperative outcome with RAG.

In their series of 5,839 patients (4,542 OG, 861 LG, and 436 RAG), Kim et al[63] found that the overall rates of complications, reoperation, and mortality were similar between the three groups. Postoperative ileus and intestinal obstruction, as well as intra-abdominal fluid collections and abscesses, occurred more frequently after open surgery, while anastomotic leakage was low, but significantly more common, after the minimally invasive approach (LG 2.1%, RAG 2.3%, OG 1.1%; P=0·017). The authors hypothesized that the higher rate of leaks in LG and RAG may be associated with the limited tactile feedback or differences in staple-line reinforcement, which is not performed in laparoscopic and robotic procedures. However, the learning curve and the possibility of uncorrected bowel rotation in a small surgical field could also have contributed to the observed differences.

D2-lymphadenectomy in RAG is easier than in laparoscopy, and seems to be as accurate as in open surgery, with the possibility of allowing the surgeon to perform enlarged resections and more complex reconstructions (ie, hand-sewn esophagojejunostomy after total gastrectomy or Roux-en-Y jejunojejunostomy).[57,64–66] Nevertheless, it has been reported in several studies that digestive restoration was performed extracorporeally through the same mini laparotomy used for specimen removal.[59,67] This hybrid–open technique was used both in gastrojejunostomy and gastroduodenostomy following distal gastrectomy, as well as in esophagojejunostomy following total gastrectomy, but had less reproducible results in Western patients with higher fat mass.

Other studies have reported the following similar results in terms of postoperative outcomes after RAG compared to LG: few differences were found in the time required for mobilization, passed flatus, and resumption of diet.[68] The LOS was shorter in patients undergoing RAG than in those having LG, but this difference was not found to be statistically significant in two meta-analyses.[59,61] However, the hospital stay for RAG was significantly shorter than that for OG and was consistent in all series.[59]

The mean operating time is commonly longer in RS than in conventional laparoscopy or open surgery.[59,67] However, in one series that excluded the initial learning curve, the authors reported a similar operating time (234 minutes versus 220 minutes).[69] Obviously, all the robotic procedures needed additional setup procedures, including docking, which often requires less than 30 minutes.[59,70] Both setup time and operative time, together with the delay caused by instrument changes, are expected to decrease as the experience of the surgical and nursing teams increases.[11,64,69–71]

In comparative studies among OG, LG, and RAG, some authors[63,72] have reported that the estimated blood loss in the robotic group was significantly lower than in the open and laparoscopic groups. Similar results were confirmed in the meta-analysis from Xiong et al,[61] whose data appear to confirm the ability of surgeons to better control bleeding when using the robotic system, compared to conventional laparoscopy.

When considering the cornerstone of oncological adequacy, most authors have reported a mean number of

nodes higher than 30, which is in line with the recommended standard for conventional open D2-lymphadenectomy.[60,71,72] In a recent meta-analysis including a total of 7,200 patients (663 RAG, 1,236 LG, 5,301 OG), Hyun et al[59] reported a statistical equivalence in the number of nodes when comparing the three approaches, even when a matched analysis for the extent of lymphadenectomy and the type of gastrectomy was carried out. Likewise, in the meta-analysis from Xiong et al,[61] there were no differences observed in the number of nodes retrieved between the RAG and LG procedures.

The majority of studies reported free resection margins at pathological examination in 100% of cases following RAG,[64,67] which likely reflects some preoperative selection bias towards patients with early-stage disease.

Although data on long-term outcomes and survival after RAG are still lacking, a paper published by Pugliese et al,[70] with a mean observation length of 53 months, reported no differences in 5-year survival between LG and RAG.

Interestingly, some authors have reported that all histologically proven N+ patients who underwent RAG started adjuvant treatment without any surgery-related delay within 30 days after surgery.[64]

According to the majority of experiences reported in the literature, RAG with limited lymphadenectomy could be indicated for cancers at the initial stages (if the patients are not eligible for endoscopic resections), while RAG with D2-lymphadenectomy is indicated for the treatment of more advanced neoplasms. However, the specific exclusion criteria for RS, as is the case for laparoscopic surgery, include intolerance to pneumoperitoneum, T4 cancers, or the presence of distant metastases.[61,73]

Liver, gallbladder, and biliary tract

Although the first laparoscopic liver resection was reported by Reich et al[74] in 1991, the minimally invasive laparoscopic approach to hepatic resection had long been underestimated due to the complexity of the vascular and biliary anatomy of the liver, the exposure difficulties, and propensity for bleeding during indirect manipulation.

However, laparoscopic liver resections have also become possible with the availability of new instruments that allow a relatively bloodless liver transection. The feasibility and safety of laparoscopic liver resections have been demonstrated by several recent studies, including a few comparative trials, providing some evidence to support the further development of this technique.[75–79]

The advantages of minimally invasive surgery are well-known. These include shorter LOS, decreased postoperative pain, rapid return to preoperative activity, improved cosmesis, and decreased postoperative ileus, together with a reduction in ascites formation in cirrhotic patients.[76]

According to an international consensus report, the best candidates for laparoscopic liver resection include only those with a surface solitary lesion of less than 5 cm (despite for malignancy) that can be removed by limited resection or left lateral sectionectomy.[80,81] Otherwise, laparoscopic major or complex hepatectomies, often including the resection of the right posterior–superior segments, have been performed selectively and mostly in specialized centers because of the intrinsic technical limitations of laparoscopy that can only be partially surpassed by the ability of the individual surgeon and/or extensive training.[80,82]

Although some large (300 patients, 103 cancerous) single-center, case-matched experiences[83] have concluded that mini-invasive hepatectomy (including major resections) compared favorably with contemporaneous open controls in terms of perioperative outcomes and oncological adequacy, a Cochrane review by Rao and Ahmed[84] reported that due to the poor quality of the scientific reports, no definitive conclusion can be drawn on the benefits or harm of laparoscopy.

As is the case for other major operations, robotics could play a role in overcoming some problems prior to the popular application of minimally invasive surgery for liver resection. For example, the robotic interface is able to help the surgeon during dissection in deep and narrow spaces and for the knotting of vascular structures. The use of robotic instruments can also resolve some life-threatening situations, such as a caval injury caused by a stapler malfunction.[85]

The indications for robotic hepatic resection range from benign or malignant lesions (hepatocellular carcinoma [HCC] and colorectal metastasis [CRM], and gallbladder cancer)[86–88] to living donor hepatectomy for transplant.[89] Previously, there was a tendency to resect benign lesions, but with increasing experience, at present, the majority of indications are for malignancies,[90–94] and amount to a few hundred cases worldwide.[88,95]

Nevertheless, the segment location of the lesion plays a more important role in the surgical decision, rather than the nature of the lesion itself. Every liver segment has been approached robotically, including the posterior segments,[96] and major hepatectomy is also amenable in this manner.[90,93,97,98] The robotic platform can lead to an easier exposition of posterior segments through a stable surgical field and view, the use of a flexible sonographic probe, and the Endowrist instruments.

The cornerstones of robotic liver surgery are represented by careful laparoscopic ultrasonographic assessment (available also as a dedicated probe with a picture-in-picture imaging in the console), control of the pedicles, and a slow-safe parenchymal transection.

Many transectional techniques are amenable to robotic employment, including those using a harmonic device,[90,96,98,99] an ultrasonic aspirator,[98,99] bipolar forceps,[90,96] electrocautery,[99] or fracture technique using robotic Maryland forceps.[100] Large veins and major pedicles were divided with the use of a stapler, and typically, the vascular and biliary elements were divided or by robot with clips and/or suture ligation, or by the assistant using a harmonic scalpel, clips, or scissor.

In two comparative studies, Berber et al[100] found no differences in the mean operation times of the robotic and laparoscopic procedures, whereas a cohort-matched study conducted by Ji et al[101] and a retrospective study conducted by Spampinato et al[102] suggested that the robotic procedure required longer operation times than laparoscopic and open resection surgeries. The mean intraoperative blood loss ranged 50–660 mL.

Three recent papers that conducted matched comparisons of robotic and laparoscopic liver resections (globally, 203 laparoscopic vs 129 robotics) failed to show significant differences between the two techniques.[94,103,104] However, the robotics technique could have facilitated the management of lesions arising from the posterior segments, thus increasing the number of patients undergoing minimally invasive resection (from 2 to 10 times) and major hepatectomies. Long-term outcomes, larger patient records, and comparative studies (with open surgery and pure laparoscopy) are not yet available.

The gallbladder is approachable in the classical way by the robotic interface, with excellent results,[105] or by using a single incision.[106] Moreover, near infrared technology (Firefly) can be of great help in the visualization of biliary anatomy.[107] However, the cost-effectiveness of robotic cholecystectomy makes its routine use highly questionable.

Pancreas

Major pancreatic surgery (pancreaticoduodenectomy, total pancreatectomy, and distal pancreatic resection) is known to be a challenge for the surgeon due to complex reconstructions and the high incidence of postoperative complications. Simpler enucleations for neuroendocrine or benign disease could also lead to the development of life-threatening fistulas or pancreatitis.

From a theoretical point of view, any effort to be less invasive would be of enormous benefit for the patients. A very original and interesting survey carried out on patients and medical personnel found a trend of preference towards laparoscopic procedures when dealing with pancreatic benign disease and towards open surgery in cases of cancer.[108]

Conversely, the intrinsic difficulties, the questionable benefits, and the relatively low incidence of pancreatic cancer, which limits the gaining of sufficient skills, have confined the use of laparoscopic pancreatic surgery to a few specialized centers.[109] For example, less than 5% of hepato-biliopancreatic procedures in a large, nationwide American database were performed by a mini-invasive approach.[110]

However, while laparoscopic distal left pancreatectomy (LDP) has reached a sufficient level of standardization, especially for benign or neuroendocrine diseases,[111–115] laparoscopic pancreatoduodenectomies (LPD), although feasible, remain confined to anecdotal experiences carried out by extremely skilled surgeons.[116–119] A 2014 review with very rigorous and statistical inclusion criteria, in which only six trials met the requirements, collected no more than 169 pancreatoduodenectomies carried out worldwide by a mini-invasive approach (laparoscopic or robotic).[120] Another more inclusive recent review[121] that assessed 638 patients who were operated on robotically or laparoscopically, or by the open approach, reported a reduced LOS and blood loss at the price of longer operative time and no difference in the incidence of fistulas. It is interesting to note that the most important review had to pool robotic cases with pure laparoscopic operations in order to reach a sufficient level of statistical power.

Similar to other complex gastrointestinal procedures, RS could help overcome many of the challenging steps of the laparoscopic approach, including biliary and pancreatic anastomosis or the preservation of the spleen.[122–126] Some surgeons[127–129] have reported more than excellent results with robotic-assisted pancreatectomies compared to the open approach. For this reason, the conversion rate seems to be lowered by robotic assistance compared to pure laparoscopy (0%–18.3%[126,130–132] vs 0%–46%[133,134]), which represents the index of better technical standardization, and the possibility of managing bleeding, challenging dissections, and any other intraoperative trouble.

One of the first large statistical studies was that published by Giulianotti et al[122] in 2010, with 134 robot-assisted pancreatic operations, including robot-assisted PD (RPD) in 60 patients. Conversion, morbidity, and mortality rates for the whole series were 10.4%, 26%, and 2.2%, respectively.

The rate of pancreatic fistula was 31.3% for PD and 20.9% after distal pancreatectomy. Only one patient was reoperated on.

Similarly, a more recent single-surgeon experience[131] reported 34 patients (representing only 14% of the total pancreatoduodenectomies carried out in the same period due to careful exclusion of complex or obese patients) operated on by RPD with a mean duration of surgery of 597 minutes and an extra cost of more than €6,000. On the other hand, the patients' oncologic parameters (harvested nodes, margins) and perioperative results were good (0% 30-day mortality and global 55% morbidity).

The largest series was that published by Zureikat et al[130] from the University of Pittsburg, which included 250 robotic pancreatic resections. Of these, 132 were RPD and 83 were robotic distal pancreatectomy (RDP), while the remaining were atypical resections, enucleations, or total pancreatectomies. The postoperative complications were recorded for 90 days. The crucial endpoints were a 30- and 90-day mortality of 0.8% and 2.0%, respectively, Clavien 3 and 4 complication rates of 14% and 6%, and the International Study Group on Pancreatic Fistula grade C fistula rate of 4%. The mean operative time for the two most common procedures was 529 minutes for RPD and 257 minutes for RDP.

A meta-analysis by Zhang et al,[135] which included seven trials, suggested that robotic pancreatectomy is as safe and efficient as, if not superior to, open surgery, although the evidence was highly insufficient. The pooled analysis compared 137 robotic and 203 open pancreatectomies, and found superior results in morbidity, redo surgery, and resection margins in the robotic group. Blood loss and LOS were also lower in the robotic group, although these differences were not statistically significant. Conversely, operating time was significantly shorter in the open group. No differences in fistula and mortality rates were evident.

Another very accurate meta-analysis[136] reported comparable results of RPD and LPD or open pancreatoduodenectomies (OPD) in terms of morbidity and mortality. However, the limits of the studies included were several and important. For example, no cost-effectiveness analysis was carried out, the techniques applied were heterogeneous, and the case series were biased by patient selection. A specific study targeted for the comparison of robotic and open total pancreatectomy reported that the former was associated with a longer mean operative time (600 minutes vs 469 minutes; P=0.014) but decreased mean blood loss (220 vs 705 ml; P=0.004).[132]

However, all these feasibility experiences represent the baseline safety profile of the techniques and should encourage the development of more rigorous trials.

In our opinion, full LPD should be abandoned in favor of the development of robotically assisted operations, with a careful comparison of the outcomes with respect to open surgery only. Early results for major pancreatic surgery appear encouraging when considering feasibility, safety, and oncological outcomes. Undoubtedly, the dexterities acquired by the use of the robotic interface could most likely extend the spectrum of the mini-invasive approach to include advanced pancreatic cancer and vascular reconstructions.

This concept is most likely less radical when considering LDP, but in cases of spleen preservation or radical dissections for cancer, the robotic option should be taken into consideration,[137–140] as it has a reported success rate of more than 95%.[135,141]

Colon and rectum

Currently, the surgical treatment of both colorectal benign diseases and malignancies has been recognized to be achievable by the laparoscopic route.[19,142,143] Laparoscopic colorectal surgery has gained widespread application worldwide, due to the impressive number of statistically robust studies that have been published, including many RCTs[144–148] with long follow-up[149–153] and meta-analyses.[154–156]

Other reasons for the larger penetration of laparoscopic colorectal surgery, compared to upper gastrointestinal and hepatopancreatic surgery, is represented by the high incidence of colorectal cancer, which permits adequate case-load with acceptable technical challenge in most of the hospitals worldwide.

On the other hand, data supporting routine laparoscopic rectal surgery is more difficult to validate. This is because the famous CLASSIC trial[147] reported inferior results without oncologic safety and a Cochrane review[157] did not assess the safety of the procedure compared to open surgery. The narrow experience of many of the surgeons participating in the initial trials could also have played a role in justifying the poor results.

However, some more recent RCTs,[158] targeted at the laparoscopic treatment of rectal cancer, have had good results in terms of oncologic safety, while others[159,160] have reported superior perioperative outcomes with respect to standard open rectal resection. A meta-analysis[161] confirmed the superiority of laparoscopic rectal resection with total mesorectal excision (TME) in the early- and medium-term period.

Surprisingly, the percentage of laparoscopic colectomies performed in many hospitals remains low because it requires a longer learning curve and a need for extensive training of surgeons.[162,163] The application of RS could resolve and reduce the learning curve problem for colonic resections although rectal resections for cancer remain challenging procedures for the novice robotic surgeon.[164–166]

The first robot-assisted colon resection using the da Vinci Surgical System was described by Weber et al[167] in 2001, and some surgeons have begun to perform robotic colorectal surgery (RCRS) routinely,[168–170] although according to a large recent American database, the percentage of robotic operations remained less than 3%.[171] The same retrospective database analysis failed to confirm the benefits of RCRS over conventional laparoscopy, except for decreased conversion rates, with a higher rate of bleeding and increased costs observed.[171]

Right hemicolectomy has been proposed as a first step for approaching RCRS in order to reduce the learning curve for more challenging procedures, such as robotic rectal resections (RRR).[166,172–174] However, the real advantages of right robotic hemicolectomy (RRH) towards the standard laparoscopic approach are less evident compared to rectal resection.

Many studies comparing laparoscopic and RRH have demonstrated that the robotic procedure is longer and more expensive, with no significant differences in the surgical clearance, morbidity, LOS, and oncological outcomes.[175–177]

D'Annibale et al[178] reported the safety and technical feasibility of RRH, with better lymph node sampling when compared to standard laparoscopy, while Bianchi et al[179] stressed the advantages of the robotic da Vinci system when performing a complete mesocolic excision with a high ligation of the vessels, in order to obtain the highest number of lymph nodes retrieved. In addition, the same author underlined the benefit of the robot during the anastomotic step that is hand-sewed intracorporeally.

Left hemicolectomy and sigmoidectomy with the da Vinci Robotic system are still associated with longer operative times and higher costs, as compared to laparoscopy.[180] However, it is likely that the robot could have a place in resolving some complex situations, such as lymph node dissection around the major vessels and the necessity of intracorporeal anastomosis.[181] Other good indications for robotic colectomy are diverticulitis with fistulae, concomitant liver resections, multivisceral resections for T4 tumors, and morbidly obese patients or patients prone to bleeding for hematologic diseases. Nevertheless, the short-term oncological outcomes are similar,[180,181] if not superior,[182] to the laparoscopic approach. A small RCT comparing robotic and laparoscopic left colectomies resulted in similar clinical results.[183] Many centers have introduced the use of robots to perform RRR to reduce the difficulties of performing a formal laparoscopic TME;[184] RRR is recognized as one of the best applications of RS.[182,185,186]

At least two different techniques to approach rectal cancer exist in the literature.[187] One involves a combination of laparoscopic (mobilization of the left colon) and robotic (pelvic dissection and TME) approaches, and this hybrid approach results in a shorter operative time.[188–191] The other technique is achieved solely by the use of the robotic technique, although through a so-called 'single docking'[192–195] or 'dual docking'[196] system.

TME carried out via the laparoscopic and robotic approaches have been compared in some nonrandomized trials, with a superior outcome for the robotic procedure in terms of nerve sparing and number of lymph nodes retrieved.[197,198] Other studies concluded that the quality of TME carried out robotically was encouraging, if not superior, to that achieved by traditional laparoscopy, in terms of prevention of sexual and urinary dysfunction, and intraoperative blood loss.[199,200]

When considering locoregional recurrences, the distance of recurrences, and total recurrences occurring, Kwak et al[201] did not find any significant difference between the two approaches. Moreover, Kang et al[202] reported no significant differences in 2-year survival following robotic, laparoscopic, and open group rectal surgeries.

Unsurprisingly, RRR is more expensive than laparoscopy[203] and is most likely equivalent in terms of short-term results.[204] Nevertheless, the good oncologic parameters (harvested nodes, margins, and recurrence) yielded following the robotic techniques has led to the consideration of RRR as safe.[191,205] A prospective, international, multicenter RCT to test robotic versus standard rectal resection is still ongoing.[206]

Only a few papers have assessed the learning curve for RRR. Specifically, Pigazzi et al[207] reported how operative time decreased after 20 consecutive procedures, while D'Annibale et al[208] obtained a decrease in mean operative time from 312.5 minutes in the first 25 procedures to 238.2 minutes in the last ten (P=0.002).

Another important issue for the development of RRR is the lower conversion rates with respect to laparoscopic

rectal resection,[209] which could lead to some reduction of global hospital costs during the learning curve, and an easier approach to ultra-low resections and lateral pelvic dissection in selected cases.

Lastly, the da Vinci platform was introduced to overcome the technical limitations of transanal endoscopic microsurgery (TEM).[210] The articulating instruments could effectively be used during a full-thickness transanal resection of a rectal polyp or neoplasm.[211,212] However, larger case series and trials are needed to validate the technique and to compare the outcomes with respect to the classical approach.

Miscellaneous gastrointestinal procedures

Many other gastrointestinal procedures have been carried out by robotic approaches, including pouch reconstruction after radical cystectomy,[213] small bowel resections, and inflammatory bowel disease surgery.[214] However, most of them still remain anecdotal experiences managed by very skilled robotic surgeons.[11]

Nevertheless, some interesting experiences with good results have been published regarding robotic bariatric surgery and sacrocolpopexy. For example, the application of the da Vinci® System during Roux-en-Y gastric bypass for morbid obesity was safe and feasible, with a reduction of the operating room time (130 minutes vs 149 minutes; P=0.02) in patients with higher body mass index and hand-sewed anastomosis.[215] Additionally, a recent review[216] article including 22 articles of poor quality and characterized by gross heterogeneity of techniques was conducted. Despite the use of the robot, most of the surgeons finished the bariatric procedures (biliopancreatic diversion, Roux-en-Y gastric bypass, and sleeve gastrectomy) with stapled anastomosis. The authors concluded that no evidence supported the use of the robot for more complex cases. Another review[217] reported comparable results between laparoscopic and robotic Roux-en-Y gastric bypass, but with higher costs associated with the latter.

One of the very few RCTs available in the literature regarding the use of the da Vinci® System was that conducted on sacrocolpopexy,[218] in which 78 women were treated randomly by robotic or laparoscopic approaches. The total operative time was significantly longer in the robotic group (67-minute difference; 95% confidence interval: 43–89 minutes; $P<0.001$), with the extra time persisting even when separating the anesthesia time, whole surgical time, and suturing. Patients in the robotic group also experienced higher pain after surgery. Unsurprisingly, the costs were greater with the robot (mean difference USD1,936). However, the two

groups had significant improvement in vaginal support and functional outcomes at 1 year after surgery. Similar results were reported in another recent RCT,[219] although the difference in costs disappeared when excluding the purchase and maintenance of the system.

Discussion

The introduction of minimally invasive techniques has transformed surgery in the past three decades. Patient benefits from mini-invasive surgery include less operative blood loss, less postoperative pain and consequently, reduced requirement of narcotics, and a shorter LOS. The better integration of minimally invasive surgery with neoadjuvant and adjuvant multimodal therapies represents another strong element.

Laparoscopy is now accepted and is most likely recognized as the gold standard in the management of some gastrointestinal procedures (ie, colonic surgery). However, our opinion is that greater development should be expected for robotics when dealing with esophageal, gastric, rectal, hepatic, and pancreatic surgery (Table 1). Moreover, robotic technology could lead to a crucial improvement of laparoendoscopic, single-site surgery, which currently requires excellent surgical skills and dexterity.[220]

The potential capabilities of new robotic technologies, including three-dimensional viewing, intraoperative guidance, training simulators, and robotics, will undoubtedly contribute to improving minimally invasive surgery.

Table 1 State of the art: the feasible approaches to gastrointestinal disease and the authors' opinions regarding future developments

District	Open surgery	Laparoscopic surgery	Robotic
Esophagus	+	++	+++
Reflux disease	−	+++	+++
Stomach (proximal)	+	+	++
Stomach (distal)	+	++	+++
Liver (major resection)	+	−	++
Liver (minor resection)	+	++	+
Liver (posterolateral segments)	+	−	++
Gallbladder	−	+++	+
Biliary tree	+	++	++
Pancreas (head)	+	−	+++
Pancreas (body–tail)	+	++	++
Pancreas (body–tail spleen preserving)	+	++	+++
Small bowel	+	+	+
Colon	−	+++	++
Rectum	−	++	+++

Note: Currently, open surgery is considered the standard and has a + by default, except in cases of colorectal surgery, reflux disease, and cholecystectomy.

Wristed instruments offering seven degrees of freedom, tremor filtering, scaled motion, stereoscopic steady view with excellent high definition, optimal working ergonomics, and avoidance of the 'fulcrum effect' are the main strengths of the da Vinci surgical system.[207,221]

Moreover, new devices, such as fluorescence in situ, picture-in-picture technology, navigation surgery through virtual reality software,[222] and EndoWrist manipulation adapted to sealing devices could increase the advantages of robotic procedures, even for pure laparoscopy. For example, indocyanine green and fluorescence imaging are currently applied for ureter localization, node mapping, biliary anatomy, and bowel vitality appraisal.[223–226]

Conversely, other robotic applications, such as telesurgery, which were considered highly appealing by the mass media, are very far from becoming widely applied.[227]

The flexibility of surgical manipulation is very important and convenient during tissue dissection, suturing, and reconstruction. The instruments used in traditional laparoscopic surgery do not have much flexibility when they are applied into the abdominal cavity. Robotic surgical systems have recently been introduced to enhance a surgeon's dexterity in the surgical field. In particular, the robot has been shown to improve nondominant hand performance[228,229] and reduce the need for extensive preemptive training in laparoscopic techniques.[56]

The major technical advantages of robot-assisted gastrointestinal surgery are appreciated during lymph node dissection, intracorporeal reconstruction, enlarged resections, and complex reconstructions. The better detection of vessels due to the greater field of view and the high precision of bleeding control can account for decreased blood loss in RS. The learning curve and reproducibility of RAS seem to be shorter and more feasible than with conventional laparoscopy. As such, robotics has the potential to contribute to the standardization and widespread application of minimally invasive surgery for the treatment of gastric cancer, making it a routine approach even in patients with advanced stages of disease.

Undoubtedly, the widespread adoption of robotic technology in gastrointestinal and other surgeries is far from becoming a reality at the present time. The three main drawbacks of RS are represented by the increased costs, longer operative times, and unproven benefits for patients.[7] The cost associated with RS was found to be higher than both the open and laparoscopic approaches.[9] This is the main limitation of RS and will be a major obstacle that needs to be overcome before widespread acceptance occurs.

Conversely, robotic technology is rapidly changing, and the many continuous technical improvements will most likely lead to some reduction in its intrinsic defects. For example, an increase in the number of market competitors will reduce the initial costs, while the mechanical developments may reduce the weight, encumbrance, and spatial limitations of the arms. On the other hand, the increased experience of each single center will lead to an increase of the total number of procedures performed yearly, thus reducing the dynamic costs for each single operation.

However, the longer operative time has many 'not surgical' explanations. Firstly, the setting up of the theater and the docking of the robot contributes to the total time. Secondly, the delay in changes in the instruments also plays a role. These two time delays are expected to decrease after a minimum of gained experience. However, it is of crucial importance that the development of a full robotic program should follow the important principles of safety and nonmaleficence, in order to guarantee the maximum safety of each patient during the learning curve.[20]

Nevertheless, only a few selected tertiary centers with the greatest surgical experience in both laparoscopy and surgical oncology have the adequate background and prerequisites for addressing the learning curve safely, although none should forego careful tutoring, monitoring, and validation of the data obtained. In order for this to happen, robotic technology needs to prove itself as significantly advantageous and the costs associated with its use will need to decrease. Multicenter, randomized, controlled trials and long-term follow-up evaluations are needed to definitively establish the oncological adequacy of RAS.

Conclusion

Robotics offers many potential technical advantages over conventional laparoscopy, including three-dimensional high-definition steady viewing, intraoperative guidance, training simulators, the use of wristed instruments with seven degrees of freedom, tremor filtration, scaled motion, and avoidance of the 'fulcrum effect'. Robotics will most likely lead to the full applicability of minimally invasive surgery benefits to the most complex surgical procedures, reducing the learning curves.

However, the widespread adoption of robotic technology in gastrointestinal and other surgeries is far from becoming a reality. The three main drawbacks of RS are represented by the increased costs, the longer operative times, and unproven benefits for patients. Most of these concerns are expected to be resolved with future studies and gaining of experience.

Disclosure

The authors declare no conflicts of interest in this work.

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