〈Review〉

Current Status and Future Potential of Robotic Surgery for Gastrointestinal Cancer

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ABSTRACT Robotic surgery has built on innovations in areas such as medical engineering and optical technology. Laparoscopic surgery has been successfully adapted for gastric, colon, and rectal cancer surgeries over the past two decades with numerous clinical trials showing oncological results comparable to those of open surgery. These trials have also shown that the laparoscopic approach shortens postoperative recovery time and decreases complication rates. Another advantage of minimally invasive techniques for the resection of gastric, colon, and rectal cancers is improved visualization of the surgical field. Despite the near absence of tactile feedback, robotic surgery has overcome many of the challenges inherent in laparoscopic surgery through features such as 3D vision, stable magnification, EndoWrist instruments, physiological tremor filtering, and motion scaling. Robotic surgery is not yet widely used in esophageal cancer surgery or in a pancreaticoduodenectomy for pancreatic cancer due to anatomical difficulties and the lack of a suitable approach.

Comparative studies of robotic and laparoscopic surgery have shown similar results in terms of perioperative management, oncologic evaluation, and functional outcomes. However, it is also true that the high cost and lack of tactile feedback in robotic surgery are major limitations in terms of current robotic technology becoming the worldwide standard for minimally invasive surgery. The future of robotic surgery will require cost reduction, the development of new

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platforms and technologies, the creation and validation of curricula and virtual simulators, and confirmation through appropriate randomized controlled clinical trials.

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INTRODUCTION

The da Vinci Surgical System, a surgical robot widely used in gastrointestinal, respiratory, cardiovascular, urologic, and gynecologic surgery as a major advance in minimally invasive surgery, was developed in the 1990s[1]. High-resolution 3D images and the EndoWrist with seven degrees of freedom of movement allowed it to overcome limitations in field of view and maneuverability. The first model was approved by the U.S. Food and Drug Administration in 2000, and now a fourth-generation model is available. The most common surgical procedures it is used for are total hysterectomies and prostatectomies, and its application has been rapidly expanding to other procedures in areas outside of the pelvic viscera[1]. Although there are some challenges, such as institutional accreditation, an increasing number of facilities are enthusiastically pursuing the use of this technology. Surgical time is gradually decreasing due to technical proficiency, and cost issues are also improving due to the mass production of forceps and devices, making robotic surgery increasingly useful for advanced surgeries. In recent years, many new surgical robots have been launched by a variety of companies[1]. This paper outlines the current and potential future significance of robotic surgery in gastrointestinal surgery.

1. Esophageal cancer

The standard treatment for esophageal cancer is perioperative chemotherapy or preoperative chemoradiation followed by a radical esophagectomy[2]. The laparoscopic-thoracoscopic approach has been widely adopted in the treatment of esophageal cancer because it offers substantial advantages over an open thoracotomy and esophagectomy[3]. The laparoscopic-thoracoscopic approach has been shown to reduce cardiopulmonary complications, decrease postoperative pain, shorten hospital stay, and improve the quality of life compared to surgery involving an open chest or abdomen[4]. Since robotic surgery is technically challenging, sufficient clinical data has not yet been accumulated for robotic surgery to be considered a standard treatment for the esophagus. Therefore, the following discussion is based on the limited knowledge available at this point in time.

Esophageal cancer differs greatly in histology and site of origin between Japan, East Asia, and the West. In Japan and East Asia, squamous cell carcinoma is most common in the cervical and thoracic esophagus, while in the West, adenocarcinoma is mainly found in the Barrett's esophageal epithelium of the abdominal esophagus[5]. The surgical approaches are naturally different, with squamous cell carcinoma requiring approaches in the cervical, thoracic, and abdominal regions[5]. On the other hand, Barrett's esophageal carcinoma often requires an abdominal or mediastinal approach, such as an Ivor Lewis esophagectomy[6, 7].

It is not easy to safely perform a robotic surgery that involves major body position changes. From this perspective, using robots in each of the cervical, thoracic, and abdominal approaches would pose difficulties. Recently, however, it has been reported that a robotic approach radical esophagectomy with radical lymph node dissection for squamous cell carcinoma has been safely performed[8]. The esophagus is a suitable target for a longitudinal approach using robotic surgery due to its anatomical characteristics[8]. Although robotic surgery can offer some advantages in esophageal cancer, there is a lack of clear, high-level evidence confirming its superiority[9]. Additionally, it is costly and is not currently considered a standard procedure.

The number of robot-assisted esophagectomies performed in the left lateral or supine position following the conventional transthoracic thoracoscopic approach has increased. Simultaneously, the number of non-transthoracic thoracoscopic procedures has also increased, with the aim of preventing postoperative pulmonary complications without compromising the performance of lymph node dissection. A radical transhiatal esophagectomy combined with a robotic-assisted transthoracic thoracoscopic transhiatal approach to the superior, middle, and middle inferior mediastinum has also been developed. This is a non-transthoracic radical esophagectomy procedure combining a video-assisted cervical approach to the superior mediastinum and a transmediastinal esophagectomy with a robot-assisted transhiatal approach to the middle and inferior mediastinum. Promising results have been reported[8].

A meta-analysis of studies comparing the results of spectroscopic and robotic esophagectomies showed similar suture failure rates, mortality rates, and length of stay for Ivor-Lewis esophagectomies[7]. However, robotic surgery was associated with less intraoperative blood loss, a lower incidence of postoperative pneumonia, lower overall complication rates, and higher radical resection rates[7]. Further high-quality studies are warranted to determine its ultimate usefulness.

2. Gastric cancer

With the widespread use of laparoscopic surgery and technological advances, D2 dissection is now performed in many facilities[10]. Lymph node dissection along the superior border of the pancreas is vital when treating gastric cancer, and must include the peripancreatic tissue, common hepatic artery, and the splenic artery. This dissection is technically challenging to perform with forceps, and so various techniques have been devised for the approach[11, 12]. Robotic forceps that can be used with a high degree of freedom are expected to help overcome the limitations of motion imposed by straight forceps.

A laparoscopic gastrectomy (LG) is a widely used minimally invasive procedure for gastric cancer[13]. The first LG for gastric cancer was reported by Kitano *et al*. in 1994 and has developed rapidly. A robotic gastrectomy (RG) for gastric cancer was first reported by Hashizume M *et al*. in 2000 and has been introduced in many institutions since then[14].

A meta-analysis by Guerrini *et al*. analyzed 38 retrospective studies comparing the results of laparoscopic and robotic gastrectomies and found that robotic surgery demonstrated efficacy, safety, and feasibility over laparoscopic approaches for patients with gastric cancer[15]. Specifically, the results confirmed that RG provided oncologic benefits comparable to the results of general surgical resection[15]. Operating time is one of the most measured surgical variables and several studies have reported that the average operating time of RG is usually longer than that of LG[16, 17]. It has been shown that operation time is usually improved along a learning curve as robotic surgical experience is acquired[18, 19]. The Guerrini *et al*. meta-analysis also confirmed that the robotic approach was associated with a significant reduction in mean intraoperative blood loss[13]. Decreased blood loss and the consequent reduced perioperative need for blood transfusions are associated with improved short-term clinical outcomes and are also associated with improved long-term oncologic outcomes[20, 21]. The relatively short learning curve for robotic surgery has also been reported to provide a more accurate procedure versus a total gastrectomy[1].

Robotic platforms are reported to help reduce blood loss due to inherent advantages such as 3D views, tremor filtering, accurate lymph node dissection, and easier vascular ligation and suturing than laparoscopic approaches[22, 23]. Reports also show no significant differences with respect to the conversion rate to open surgery, the need for reoperation, or postoperative mortality. The most common causes of conversion to a laparotomy were technical difficulty, dense adhesions, and injury to adjacent organs[24, 25]. The advantages of magnified 3D views and stable motion facilitated accurate dissection and avoidance of adjacent organ damage[24, 25].

Differences between robotic and laparoscopic gastrectomies in terms of postoperative complication rates were also analyzed. The Guerrini *et al.* meta-analysis showed that the incidence of major postoperative complications in RG surgeries (4.13%) was significantly lower than in LG surgeries (6.44%)[15].

3. Colorectal cancer

There are no absolute contraindications to robotic colon and rectal cancer surgery, and its application is primarily dictated by a surgeon's experience and expertise[1, 26, 27]. Relative contraindications are locally invasive tumors and recurrent disease, which often require approaches that differ from normal anatomy. Currently performed robotic surgeries are based on a number of clinical trials that have shown oncological results comparable to those of open surgery[26, 27]. Robotic colorectal surgery was first reported on in 2001, and the first robotic total mesorectal excision was performed in 2006. The slow expansion of robotic surgery in colorectal surgery is due to insufficient high-level evidence of its superiority over laparoscopic surgery and its high cost[1].

Widespread adoption of robotic colon resection requires evidence of the equivalence or superiority to existing approaches regarding safety, feasibility, and outcomes, and a number of such reports have been published[28−37]. The robotic approach, however, had a significantly longer operative time, which may be related to a higher frequency of in vivo anastomosis. The total hospital costs of robotic surgery were reported to be about 16% higher ($12,235 vs. $10,319)[32, 38]. Park *et al.* reported no significant differences in estimated blood loss, conversion rates, stay duration, surgical complications, postoperative pain, resection margins, or the degree of lymph node dissection[34]. Similarly, a single-center retrospective study of right colon resection by deSouza *et al.* found no difference in conversion rate to open surgery, positive resection margin rate, lymph node yield, length of stay, or morbidity between robotic and laparoscopic procedures[32, 38].

Complication rates after robotic surgery for rectal cancer are comparable to those of laparoscopic surgery. Published meta-analyses have found that hospital stay, complication rates, suture failure rates, and reoperation rates are comparable between robotic and laparoscopic surgery for rectal cancer[39−45]. Conversion rates to open surgery were consistently lower for robotic surgery (1.1-3%) than for laparoscopic surgery (6-7.5%), suggesting that the robotic platform may enhance the ability of a surgeon to complete more difficult cases[39−45].

4. Pancreatic cancer

Robotic surgery in pancreatic cancer surgery is gradually progressing, including for cancer in the head of the pancreas. Robotic surgery to resect cancer in the pancreatic body and tail is relatively simple to implement from a technical skill perspective because there is no need for reconstruction[46]. On the other hand, for cancer in the pancreatic head, it is necessary to perform a pancreaticoduodenectomy which requires proficiency in complex, highly technical reconstructive procedures. The surgeon must be highly skilled to perform the pancreatic jejunal anastomosis and bile duct jejunal anastomosis under the abdominal cavity. Compared to conventional laparoscopic surgery, robots are considered to be well suited for such gastrointestinal reconstructive procedures because of their optical field of view and the precision of the approach needed for the devices used for suturing. Therefore, a robotic pancreatoduodenectomy is currently considered to be a procedure that should be performed only at institutions that are skilled in both robotic and pancreatic surgeries[47, 48]. Despite the level of difficulty, robotic assistance in pancreatic surgery has several advantages including three-dimensional visualization of the peripancreatic anatomy, optical magnification of major vascular structures, stabilization of tremors, and nearly 540 degrees of robotic instrument joint motion[1]. These technical advantages are reflected in a reduced rate of open conversion compared to conventional laparoscopic surgery[49].

No large, high-quality randomized controlled pancreaticoduodenectomy trials were found during our research. However, Liu *et al*. did examine the usefulness of a new single-layer sequential suture (SCS) for pancreatic jejunal anastomosis during a pancreaticoduodenectomy compared to conventional methods. There were no significant differences between the SCS and control groups in terms of operative time, estimated blood loss, postoperative hospitalization, conversion rate to open surgery, morbidity, reoperation, or mortality. In a subgroup analysis of patients with a soft pancreas and a small main pancreatic duct, SCS significantly reduced the duration of jejunal anastomosis and did not increase the incidence of clinically relevant postoperative pancreatic fistula[1].

5. Hepatic cancer

A minimally invasive hepatectomy can be both fully laparoscopic and fully robotic. The number of laparoscopic hepatectomies is rapidly increasing worldwide. Initially, the most preferred indication for a minimally invasive hepatectomy was solitary lesions with a tumor size less than 5 cm, located in the left and/or anterior part of the liver[50]. Currently, a left lateral sectionectomy is recommended as the standard procedure[51]. Since the first robotic liver resection (RLR) was performed in Italy in 2003[52], many case reports have been published[53], highlighting the usefulness of the robotic approach[54]. Both laparoscopic and robotic approaches have been applied to a variety of liver resections. Several meta-analyses have published results comparing robotic versus open liver resection, showing that RLR significantly decreases overall complications, blood loss, blood transfusions, reduces hospital stay by 3 to 5 days and is nearly equivalent in terms of tumor control[55, 56]. Ziogas IA *et al*. reported laparoscopic major hepatectomy and robotic major hepatectomy have equivalent peri-/postoperative outcomes when performed in select patients and high-volume centers in their meta analysis[57].

Some theoretical advantages of robotic technology include safety from minimizing surgeon tremor, visual magnification, and improved accuracy[58]. For experienced liver surgeons who are only familiar with the open approach, the learning curve for robotic surgery is considered slower than for conventional laparoscopic surgery[58, 59].

Although robotic assistance cannot improve all clinical outcomes, the robotic approach is preferred for complex cases, such as tumors that are near major blood vessels, obesity, and cases of abnormal hepatic artery travel[60]. At the time of robot introduction, the advantages of using a robotic system for minor hepatectomy are not small for liver surgeons who are inexperienced in robotic surgery.

CONCLUSIONS

The surgeons and developers are rapidly implementing new technologies to improve on the capabilities of previously established systems. Although further investigations are required to evaluate the advantages and problems of robotic involvement in the operation systems, initial data have shown that robotic-assisted platforms are able to provide comparable results relative to conventional procedures.

CONFLICTS OF INTEREST

The authors have no conflicts of interest to disclose.

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