

Robotic Foregut Surgery

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1. Introduction

Laparoscopy and minimally invasive operative techniques revolutionized abdominal surgery, beginning with the first laparoscopic cholecystectomy in 1987 (Mouret, 1996). Patients, surgeons, and industry alike have promoted the application of these techniques to a wide range of procedures. Smaller incisions and less abdominal wall trauma contribute to improved cosmesis, shorter hospitalizations, less pain, and quicker recovery than is observed following open procedures. Laparoscopic techniques have been widely adopted in a variety of foregut procedures. The laparoscope has allowed surgeons to visualize areas that are more difficult to see in standard open procedures such as the gastroesophageal junction or the diaphragmatic hiatus. These factors have contributed to a population-based rate of antireflux surgery that more than doubled in the United States between 1990 and 1997 (Finalyson, *et al*, 2003).

Several limitations inherent to a laparoscopic approach have prevented its widespread use in some areas of general surgery. The visualization during laparoscopic surgery is typically two-dimensional and limited by camera operator fatigue and abrupt movements. There is diminished tactile feedback, and complex maneuvers are difficult secondary to fixed trocar position and non-articulated instruments. In addition, the length of the instruments amplifies one's natural tremor at the tip of the instrument. During a standard laparoscopic procedure, surgeons frequently must stand in ergonomically awkward positions for extended periods of time.

Surgical robots, or computer-assisted telemanipulators as they are more properly described, allow the surgeon to overcome many of these limitations. Ergonomics are improved as the surgeon sits at a console remote from the patient and manipulates controls for the surgical instruments. The computer eliminates tremor and scales all motions to a selected degree. This allows for very fine and precise movements of the surgical instruments. Since the robotic instruments are multi-articulated and capable of a full range of motion, complex maneuvers are possible. These articulated instruments provide movements similar to the human arm and hand. In addition, high-definition, three-dimensional visualization provides image detail and depth superior to that of a standard laparoscopic system. The camera is manipulated by a robotic arm controlled by the operating surgeon. These features translate to certain advantages during complex foregut procedures when compared to a standard laparoscopic approach.

2. Surgical Robotic Systems

The AESOP system was the first robotic device approved for clinical use by the Food and Drug Administration (FDA) in 1994. The acronym AESOP stands for *Automated Endoscopic System for Optimal Positioning*. This device was developed with research funding from the Pentagon's Defense Advanced Research Projects Agency (DARPA) program. AESOP holds the laparoscope steady without wandering, distraction, or fatigue. The laparoscope and AESOP can be redirected manually by the surgeon. Initially, AESOP functioned via a foot switch or hand control, but eventually voice activated manipulation became standard. AESOP connects to the side of any standard operating table and can accept any rigid laparoscope. While solo surgeon procedures are facilitated with this system, AESOP moves much more slowly than a skilled assistant, which contributed to its limited use by surgeons. The Zeus robotic surgical system was FDA approved for use in abdominal operations in the United States in 2001. Zeus utilized the AESOP system for camera navigation along with two additional multi-articulated robotic arms. Zeus is no longer commercially available. At the time of this writing, the da Vinci robotic surgical system (Intuitive Surgical, Sunnyvale, CA, USA) is the only FDA approved and commercially available robotic system. Da Vinci has received FDA approval for a wide variety of applications including cardiac, thoracic, gynecologic, urologic, and abdominal procedures. This system consists of an operating console, a patient-side cart, and a tower for the insufflator and video electronics. The surgeon sits at the operating console remote from the patient, but usually within the same room. The surgeon's head rests on the console where a high definition, three-dimensional stereoscopic images is displayed. While in this position, the surgeon is able to manipulate the camera and two or three robotic arms in a more natural and ergonomic position than is often possible during standard laparoscopy. The surgeon can toggle manual controls between the camera and any two of the 3 additional arms. The da Vinci's surgical instruments are designed to mimic the dexterity of the human wrist with a full seven degrees of freedom. This provides greater control when performing fine tissue dissection or complex technical procedures when compared to a standard rigid laparoscopic instrument. There are several limitations to the da Vinci surgical system. The surgeon is provided with essentially no haptic or tactile feedback. Visual cues are necessary to judge tissue tension during dissection or suturing. The da Vinci system is capable of generating a tremendous amount of force, which can be particularly dangerous when movements are made outside of the visual field. The patient side cart and console are large and occupy a lot of floor space in the operating room. The size of the patient side cart limits access by additional personnel (i.e., anesthesiology, circulating nurses) during the procedure to the patient. Once the robot is engaged to the cannulas, the table or patient cannot be repositioned without disengaging the robot. The da Vinci system is also quite expensive and requires specialized instruments with a limited number of uses controlled by the computer. This has been a major factor preventing the wide-spread dissemination of this technology in operating rooms throughout the world.

3. Antireflux Surgery

Laparoscopic antireflux procedures require an advanced set of surgical skills. A surgeon must be adept at fine dissection and suturing. Nissen fundoplication was among the first procedures to be performed robotically. The first two cases of robotic fundoplication were

reported by Guy Bernard Cadiere in 1999 (Cadiere, *et al*, 1999). A subsequent prospective randomized trial by Cadiere and colleagues included 21 patients to undergo either a robotic or a laparoscopic Nissen fundoplication. While patients in each study group had similar blood loss, length of stay, and perioperative morbidity, mean operative time was significantly increased (72 vs. 52 minutes; $p < 0.01$) in the robotic patients. The authors commented on some difficulties with instrument manipulation and decreased visualization during the robotic cases. These procedures were performed on an earlier version of the da Vinci robotic system known as Mona (Cadiere, *et al*, 2001).

Melvin's group performed a prospective, non-randomized comparative trial of robotic versus standard laparoscopic Nissen fundoplication. Outcomes for the first 20 robotic fundoplications were compared with a group of twenty consecutive laparoscopic fundoplications. On average, the robotic cases took 45 minutes longer. Clinical outcomes, assessed at follow-up by a survey, were similar in the two groups (Melvin, *et al*, 2002). Morino randomized 50 consecutive patients to either robotic or a standard laparoscopic Nissen fundoplication. Total operative time and skin-to-skin time were significantly shorter for conventional laparoscopy. These authors examined the 'learning curve' for robotic cases and determined that there was no difference in the operative time for the first ten and final ten robotic procedures. These surgeons felt that the increased operative time was secondary to robot set-up time, more difficult trocar positioning, and increased time taken to suture the wrap. The cost of the robotic procedure was significantly higher than that for standard laparoscopic fundoplication (euros 3151 vs. euros 1527; $p < 0.001$). There were no differences in outcomes based on clinical, endoscopic, or functional assessment (Morino, *et al*, 2006).

Nakadi performed a prospective randomized study to compare the benefits and costs associated with laparoscopic and robot-assisted Nissen fundoplication in 20 patients. Robot-assisted Nissen fundoplication was associated with longer operative times and higher costs compared to the laparoscopic approach. Increased cost for the robot-assisted cases was related to many causes ranging from the initial investment and maintenance, to nursing costs, to the costs for the specialized robotic instrumentation with a limited number of uses (Nakadi, *et al*, 2006).

Several other authors have examined the issue of the impact of a robotic-assisted approach on operative times for fundoplication. Lehnert demonstrated that performing the robotic Thal fundoplication in children took a significantly longer amount of time (Lehnert, *et al*, 2006). When the times were further analyzed, it was clear that time for setup of the robot was significantly longer (20.8 ± 7.5 vs. 34.6 ± 9.2 minutes, $p < 0.05$), but that the actual time to completion of the fundoplication was significantly shorter (30.8 ± 8.7 vs. 20.2 ± 5.3 minutes, $p < 0.05$). Recently, Muller-Stich and colleagues reported the results of their prospective randomized trial including 40 patients to undergo either conventional laparoscopic fundoplication or a robotic-assisted fundoplication. Contrary to what was observed in several previous trials, the total operative time was shorter for robotic-assisted compared to laparoscopic fundoplications (88 vs. 102 min; $p = 0.033$). Robotic cases in this series took longer to set-up (23 vs. 20 min; $p = 0.050$) but involved a shorter effective operating time (65 vs. 82 min; $p = 0.006$). Outcomes were similar for each technique, but costs were significantly higher for robotic cases (euro 3244 vs. euro 2743, $p = 0.003$). These investigators concluded that in experienced hands, robotic Nissen fundoplications can be performed faster than conventional laparoscopic fundoplications, but that given the increased cost and equivalent outcomes, laparoscopy should be the preferred choice (Muller-Stich, *et al*, 2007).

Currently, the literature suggests that the robotic-assisted antireflux surgery is as safe and effective as a traditional laparoscopic approach. Computer-assisted fundoplications may be associated with an increased operative time and a higher cost than a traditional laparoscopic approach. At the current level of technology, computer-assisted antireflux surgery does not appear to offer major clinical advantages to patients with skilled and experienced laparoscopic surgeons.

4. Heller Myotomy

Achalasia is a relatively rare condition which can lead to dysphagia and other symptoms related to impaired esophageal emptying. Laparoscopic Heller myotomy has become a standard treatment option for achalasia and has been demonstrated to be effective in greater than 90% of patients. Occasionally, during the course of a myotomy, mucosal perforation occurs. The incidence of mucosal perforations is approximately 5% (Finley, *et al*, 2001). If recognized at the time of the procedure, it is unlikely that the outcome will be affected by this perforation. However, a perforation does require time and advanced laparoscopic suturing skills to repair. Theoretically, robotic surgical systems offer several advantages over traditional laparoscopic Heller myotomy. Three-dimensional imaging and more precise and complex movements may contribute to a decreased incidence of mucosal perforation, and if one should occur, robotic systems may facilitate precise mucosal reapproximation and secure repair.

A multi-institutional retrospective study published in 2005 demonstrated that the mean operative time for robotic-assisted Heller myotomy and partial fundoplication was 140.5 minutes in a series of 104 patients. This operative time decreased from 162.6 minutes to 113.5 minutes when the time periods of 2000-2002 and 2003-2004 were compared ($p=0.0001$). In this study, there were no esophageal mucosal perforations. (Melvin, *et al.*, 2005).

In a prospective, non-randomized study of 121 patients comparing laparoscopic to robotic-assisted Heller myotomy, Horgan demonstrated that operative time was significantly longer in the robotic group (141 vs. 122 minutes, $p<0.05$). Perhaps demonstrating the effect of the 'learning curve', in the last 30 cases, there was no difference in the operative times between the two groups (108 vs. 104 minutes, $p=NS$). There were no mucosal perforations in the robotic group compared to 16% rate in the laparoscopic group ($p<0.01$). Successful relief of symptoms was 90% at 22 months and did not vary based on study group (Horgan, 2005). A recent case series demonstrated similar findings in regards to mucosal perforation rates for robotic myotomy. When comparing 19 robotic myotomies with 51 laparoscopic myotomies, the mucosal perforation rate was 0% for robotic compared to 7.8% for laparoscopic myotomy (Iqbal, *et al*, 2006). Galvani and colleagues found that of 54 patients undergoing robotic Heller myotomy between September 2002 and February 2004, the average operative time was 162 minutes, there were no mucosal perforations, and 93% of patients had symptomatic relief at 17 months follow-up (Galvani, *et al*, 2006).

Based on the results of these published studies, it would appear that robotic-assisted Heller myotomy is safe and effective. Robotic technology may help to decrease the rate of esophageal mucosal perforations. Presumably, this relates to the superior three-dimensional visualization and more complex and precise maneuvers possible with computer-assisted surgical systems.

5. Bariatric Surgery

Morbid obesity is becoming an increasingly prevalent condition world wide. In the United States, obesity is the second leading cause of preventable death (Ogden *et al*, 2002). Many significant medical conditions are associated with obesity including hypertension, diabetes mellitus, heart disease, sleep apnea, osteoarthritis, and hyperlipidemia among others. Bariatric surgery has been demonstrated to lead to significant and durable weight loss, with an improvement or resolution of these obesity-related medical conditions in many cases. Minimally invasive bariatric surgery has several significant advantages when compared to the open approach including a decrease in wound infections, hernias, pulmonary complications, and a shorter hospital stay (Ngyun *et al*, 2001). Laparoscopic bariatric surgery is a complex procedure with a steep learning curve. Computer-assisted surgical devices may be useful tools for these difficult procedures.

Jacobsen demonstrated the advantages of robotic-assisted gastric bypass in 2003. An informal survey of 11 surgeons performing robotic-assisted gastric bypass was conducted. In 107 cases, no anastomotic leaks were reported. The surgeons found this technology useful for several reasons. The three-dimensional view, instruments with articulating 'wrists', and motion-scaling facilitated the construction of a hand-sewn gastrojejunostomy. Several surgeons to respond to this survey felt that this fact may have allowed for the construction of a smaller gastric pouch than is possible with a traditional stapled gastrojejunostomy. Another perceived advantage was that the stiffer robotic instruments did not bend like a conventional laparoscopic instrument might during minimally invasive gastric bypass in especially obese patients with a very thick abdominal wall. Operative times were longer for robotic-assisted procedures compared to traditional open or laparoscopic techniques in the experience of the surgeons to complete this survey (Jacobsen, *et al*, 2003).

Ali and colleagues reported their experience with 50 robotic-assisted laparoscopic Roux-en-Y gastric bypasses (RYGB). In this series, the robotic system was used only for the construction of the gastrojejunostomy using robotic suturing techniques. The remaining portions of the procedures in this series were performed using conventional laparoscopic and stapling techniques. The robot setup time and total operative time decreased as the authors gained experience. Two complications were observed including one anastomotic leak repaired at the time of the original operation, and a gastrojejunostomy stenosis. (Ali, *et al*, 2005).

Docking the patient side robotic cart and setting up this device takes time. With experience, surgical teams have demonstrated that this robot set-up time can be minimized. While robot set-up is a time commitment not required for a case performed using standard laparoscopic techniques, some authors have demonstrated that overall operative times can be decreased for certain procedures when performed robotically. Presumably, this is related to the superior maneuverability and dexterity of robotic surgical instruments. One thought is that this may facilitate and simplify the performance of complex tasks such as suturing. Mohr and colleagues compared their operative times and perioperative complication rates for their first ten totally robotic RYGB cases with a retrospective matched sample of ten patients undergoing RYGB using conventional laparoscopic techniques. The median surgical time (169 vs. 208 minutes; $p = 0.03$) and median operative time divided by body mass index (BMI) (3.8 vs. 5.0; $p = 0.04$) were significantly lower for the totally robotic procedures (Mohr, *et al*, 2005). This same group also reported a retrospective review of the operative times and complication rates for their first 75 totally robotic RYGB procedures.

Results were compared between three minimally invasive surgery fellows in order to determine the 'learning curve' for totally robotic RYGB. Each laparoscopic fellow reached a five case running average metric of 3.5 min/BMI by 6th, 7th, and 9th case, with a learning curve of 10-15 cases. This was significantly faster than that of laparoscopic RYGB where the authors averaged 3.7 min/BMI for their first 100 cases, 2.9 min/BMI for their second 200 cases. The authors of this study conclude that totally robotic RYGB is superior to laparoscopic RYGB and that is associated with a faster learning curve (Mohr, *et al*, 2006).

Sanchez and colleagues randomized a new laparoscopic surgery fellow's first 50 cases to either laparoscopic or totally robotic. While there was no differences in age, gender, comorbidities, complication rates, or length of stay; the mean operating time was significantly shorter for the robotic group (130.8 versus 149.4 minutes; $p = 0.02$). Additionally, they demonstrated a significant difference in minutes per BMI (2.94 versus 3.47 min/BMI; $p = 0.02$). The largest difference was in patients with a BMI $> 43 \text{ kg/m}^2$, for whom the difference in procedure time was 29.6 minutes (123.5 minutes for robotic versus 153.2 minutes for laparoscopic; $p = 0.009$), with a significant difference in minutes per BMI (2.49 versus 3.24 min/BMI; $p = 0.009$) (Sanchez, *et al*, 2005).

Robotic performance of bariatric procedures including adjustable gastric banding and biliopancreatic diversion has also been reported. During the course of placing an adjustable gastric band, multiple gastro-gastric sutures are placed in the anterior, proximal gastric wall. This can be quite technically challenging due to poor visualization and ergonomic conditions in some patients. Horgan and colleagues reported operative outcomes for 32 robot-assisted adjustable gastric band placements. Robotic gastric band placement had a lower complication rate and a similar length of stay as gastric bands placed with conventional laparoscopy. Operative times were greater for robotic-assisted cases. These surgeons felt that the robotic system was especially useful in the super obese patient population who can often have a very thick abdominal wall. (Moser and Horgan, 2004). The biliopancreatic diversion is a technically challenging laparoscopic procedure which can require quite a bit of suturing. Sudan and colleagues recently published their experience with robotic biliopancreatic diversion. In a series of 47 patients, the mean operative time was 514 min (range, 370-931 min). The median operative time for the last 10 patients was 379 min (range, 370-582 min). All anastomosis in these cases were performed using robotic suturing techniques. Three patients underwent conversion to open surgery, and four patients experienced postoperative leaks with no mortality (Sudan, *et al*, 2007). Robotic surgical systems with their improved ergonomics and multi-articulated instruments seem ideally suited to very long procedures requiring lots of suturing such as these cases.

The relevant literature suggests that robotic-assisted bariatric surgery is feasible and safe. It is possible that robotic surgical systems may help to shorten the learning curve for surgeons just getting started in minimally invasive bariatric surgery. For experienced surgical teams, it is also possible that these systems may help to decrease operative times, particularly for cases where a lot of suturing is required. Surgery in patients with an elevated BMI or very thick abdominal walls may also be more easily accomplished. Further research and experience is necessary to determine the exact role of robotics in bariatric surgery.

6. Esophagectomy

Esophagectomy is a procedure that can have a high morbidity and mortality rate. Although the optimal surgical approach to esophagectomy remains controversial, the two most

frequent approaches within the United States are transhiatal and transthoracic. Minimally invasive surgical approaches to esophagectomy have been reported. These involve laparoscopic and thoracoscopic techniques. Horgan and colleagues reported their initial experience with a case of robotically assisted transhiatal esophagectomy in 2003. The total operative time was 246 minutes and the patient lost less than 50mL of blood. There were no major perioperative complications. It was believed that the three-dimensional image and the articulating wrists allowed them to perform a nearly bloodless dissection of the esophagus. In addition, they found that they could mobilize the esophagus beyond the level of the carina through a trans-abdominal robotic approach. These surgeons felt that this was due to the fact that the robotic instruments are 7.5 cm longer than standard laparoscopic instruments. A thoracoscopic approach to complete esophageal dissection and mobilization was avoided in this case (Horgan, *et al*, 2003).

Gutt and colleagues recently reported their experience with a robotic-assisted trans-hiatal esophagectomy in a patient who had lower esophageal cancer and was a high medical risk for surgery. Esophageal resection and reconstruction was possible without intraoperative incident and with minimal blood loss (Gutt, *et al*, 2006). Van Hilleberg and colleagues reported their initial experience with robot-assisted thoracoscopic esophagectomy (RTE) with mediastinal lymphadenectomy. Twenty-one consecutive patients with esophageal cancer who underwent RTE with the da Vinci robotic system were evaluated. A total of 18 (86%) procedures were completed thoracoscopically. Robot-assisted thoracoscopic esophagectomy was found to be feasible and safe (van Hilleberg, 2006).

Recently, Kernstine and colleagues detailed their initial experience with totally robotic esophagectomy with a three field lymphadenectomy. A total of 14 patients with a median age of 64 years underwent esophagectomy using the da Vinci robot. Group 1 consisted of the first three patients in the series, whose surgery was robotically-assisted in the thoracic portion only (robotically assisted esophagectomy). Group 2, the next three patients, had robotically assisted thoracic esophagectomy plus thoracic duct ligation and a laparoscopic abdominal portion with creation of a gastric conduit. Group 3, the last eight patients, underwent completely robotic esophagectomy. It was noted that the total operating room time was 11.1 +/- 0.8 h (range, 11.3-13.2 h), with a console time of 5.0 +/- 0.5 h (range, 4.8-5.8 h). The estimated blood loss was 400 +/- 300 ml (range, 200-950 ml). In this initial series, the operating room time was quite long. The console time or surgical robotic time of 4.9 h was similar to the transhiatal operative time of 4.2 h and less than the operating time of 7 h for the open three-field approach. The authors estimate that the robot docking, neck exposure, feeding tube placement, and esophagogastric anastomosis requires 1.5 h, the resultant true surgical time is estimated to be 6.4 h (4.9 +1.5 h), which leaves nearly 5 h of non-surgical time. To minimize the operating room time and improve efficiency, they felt several steps needed to be taken. These steps include the development of a focused robotic operating team, the use of an experienced surgical assistant and anesthesiologist, precise initial port placement and minimizing the frequency of robotic instrument changes (Kernstine, *et al*, 2007).

While experience with this technique is limited, it appears to be safe. Robotic instruments that are long and multi-articulated may facilitate the completion of minimally invasive esophagectomy to a greater degree than conventional rigid laparoscopic instruments. Further research and clinical experience in this area will be necessary to answer these questions.

7. Future Applications

The future of robotics in foregut surgery seems to be bright. Remote telesurgery is a concept where the surgeon manipulating the robotic controls is separated by a distance from the patient. Marescaux and colleagues performed the first transatlantic robotic procedure in 2001 (Marescaux et al., 2001). They successfully removed the gallbladder of a woman in France from New York. Surgeons from McMaster University in Hamilton, Ontario and North Bay General Hospital 400 km north of Hamilton have established a robotic telesurgical service. Twenty-two procedures were performed including 13 funduplications, 4 sigmoid resections, 3 right hemicolectomies, and 2 hernia repairs (Anvari, 2007). One of the major limiting factors, and a safety issue, relates to signal latency. Latency is the time between when the robotic master controllers are maneuvered, and when the remote robotic arm itself moves. In the experience with remote telesurgery, Anvari observed that a latency of greater than 200 msec required excessive and distracting compensation by the operating surgeon. In the future, with the development of larger and faster signal transfer capabilities, latency will be reduced and telesurgery may become more common. The technology is not the only issue that will need to be addressed before telerobotic foregut surgery becomes commonplace. Many legal and ethical dilemmas arise and will need to be considered carefully.

In vivo robots are miniature, self-propelled devices that can be placed into body cavities to perform certain tasks. At the University of Nebraska, investigators have successfully deployed small robots trans-gastrically into the peritoneal cavity to navigate, visualize, and to grasp or manipulate tissue. (Rentschler and Oleynikov, 2007). These miniature robots are currently in the early stages of development, but hold great promise for the future. Some day, foregut surgery without incisions may be facilitated by these miniature robotic devices deployed from a natural orifice.

Robotic surgical systems of the future may be integrated with sophisticated imaging systems. Preoperative and intraoperative radiographs may help guide a surgeon, or possibly even allow the robotic surgical system to perform parts of selected procedures autonomously.

8. Conclusion

Robotic-assisted foregut surgery is an evolving field with an exciting future. There are many potential advantages to robotic foregut surgery when compared to the conventional laparoscopic approach. The magnified, 3-dimensional image allows for a better view of the operative field and may facilitate the identification and dissection of anatomy. The full range of motion, tremor filtration, and motion scaling afforded by the robotic surgical system can enhance a surgeon's skill, possibly leading to better clinical outcomes and less fatigue. As demonstrated, these relatively new techniques may provide a clinical advantage to surgeons performing esophagectomy, esophageal myotomies, or bariatric procedures. In addition, robotic assistance may in the future allow expert laparoscopic surgeons to assist on procedures performed in remote settings. As robotic technology evolves and disseminates to more operating rooms, it is likely that robotic foregut surgery will become more common.

9. References

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