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REVIEW ARTICLE

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Prince and princesses: The current status of robotic surgery in surgical oncology

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Abstract

Robotic surgery has experienced a dramatic increase in utilization across general surgery over the last two decades, including in surgical oncology. Although urologists and gynecologists were the first to show that this technology could be utilized in cancer surgery, the robot is now a powerful tool in the treatment of gastrointestinal, hepato–pancreatico–biliary, colorectal, endocrine, and soft tissue malignancies. While long-term outcomes are still pending, short-term outcomes have showed promise for this technologic advancement of cancer surgery.

KEYWORDS

robotic colectomy, robotic esophagectomy, robotic gastrectomy, robotic hepatectomy, robotic pancreas surgery, robotic total mesorectal excision

1 | INTRODUCTION

Cancer is a leading cause of mortality worldwide, with nearly 10 million deaths related to cancer in 2020.[1] In the United States, over $100 billion dollars are spent caring for patients with cancer, a number only projected to increase.[2] The treatment of cancer is ever evolving, with ongoing advancements in chemotherapy, radiotherapy, immunotherapy, regional therapy, and surgery. Surgical oncologists aim to remove malignant tumors safely and effectively, maximizing oncologic principles while minimizing surgical trauma, with the overall goal of improving patient quantity and quality of life. Compared to open surgery, minimally invasive surgery provides patients with the benefits of reduced blood loss, less pain, shorter hospital stays, and in some cases, less complications.[3] As Dr. Blake Cady famously said "biology is King and selection of cases is Queen, and the technical details of surgical procedures are princes and princess." Understanding the current status of the princes and princesses in cancer surgery with the highest level of evidence is part of the job of a surgical oncologist.

Over the last two decades, minimally invasive techniques for the treatment of solid organ tumors were developed and implemented, first via a laparoscopic approach, followed soon after by robotic surgery. The introduction of the robotic platform at the turn of the century helped to overcome limitations associated with laparoscopic

Abbreviations: ACS-NSQIP, American College of Surgeons National Safety and Quality Improvement Project; DFS, disease free survival; eNSM, endoscopic nipple-sparing mastectomy; laTME, laparoscopic total mesorectal excision; LC, laparoscopic colectomy; LDP, laparoscopic distal pancreatectomy; LG, laparoscopic gastrectomy; LH, laparoscopic hepatectomy; LN, lymph node; LOS, length of stay; LPD, laparoscopic pancreaticoduodenectomy; LRP, laparoscopic radical prostatectomy; MIDP, minimally invasive distal pancreatectomy; MIE, minimally invasive laparoscopic esophagectomy; NCDB, National Cancer Database; ODP, open distal pancreatectomy; OE, open esophagectomy; OG, open gastrectomy; OH, open hepatectomy; OPD, open pancreaticoduodenectomy; ORP, open radical prostatectomy; OS, open survival; OTE, open transthoracic esophagectomy; oTME, open total mesorectal excision; PSM, propensity score matching; RAMIE, robot-assisted minimally invasive esophagectomy; RARP, robot-assisted radical prostatectomy; RC, robotic colectomy; RCT, randomized controlled trial; RDP, robotic distal pancreatectomy; RG, robotic gastrectomy; RH, robotic hepatectomy; rNSM, robotic nipple-sparing mastectomy; RPD, robotic pancreaticoduodenectomy; RR, relative risk; RT, robotic thyroidectomy; rTME, robotic total mesorectal excision; TOETVA, transoral endoscopic thyroidectomy vestibular approach; TORT, transoral robotic thyroidectomy.

surgery.[4] These advancements include high-definition three-dimension visualization, wristed instruments, stabilization of tremor, reduced operator fatigue and improved ergonomics.[5] Despite the known advantages of minimally invasive surgery, there is limited long-term evidence to support its use over traditional approaches in cancer surgery. Furthermore, a robotic approach is almost universally associated with a prolonged operative time and higher cost when compared to a laparoscopic approach.[6] Critics of robotic surgery argue that its use will only be justified with proof of superior functional and oncologic outcomes. While the current literature on the feasibility, safety, and short-term outcomes supports the use of robotic surgery in surgical oncology, there is a lack of knowledge of the impact of robotic surgery on long-term oncologic outcomes.

Despite ongoing skepticism, there has been dramatic dissemination and utilization of the robot throughout surgery, including surgical oncology.[7] This review will address the current use of the robotic platform in surgical oncology, with specific focus on the use of the robot in urologic, gastrointestinal, hepato-pancreatico-biliary, colorectal, endocrine, breast and gynecologic surgery. Where available, published randomized controlled trials (RCT) comparing a robotic approach to an open or laparoscopic approach are discussed. The current limitations and future directions of the use of the robot in the treatment of solid organ malignancies will be delineated.

2 | UROLOGIC ONCOLOGY

It is said that the development of robotic surgery aimed for the heart and hit the prostate. Although initially developed for cardiac surgery, limited acceptance of the robot amongst cardiac surgeons stalled its adoption.[8] Instead, robotic surgery gained early favor in urology for use in prostate surgery. The robot proved to be advantageous for operating minimally invasively in the pelvis and the first robot-assisted radical prostatectomy (RARP) was described in 2001 by Abbou et al.[9] Following adoption of the robot for prostate cancer surgery, it has been successfully used to treat other urologic cancers, including bladder cancer and renal cell carcinoma.

2.1 | Robotic prostatectomy

Prostate cancer is the most common non-cutaneous malignancy in the United States and it is estimated that there will be over 280,000 new diagnoses of prostate cancer in 2023.[10] Nearly one-third of patients diagnosed with prostate cancer undergo radical prostatectomy.[11] With these numbers, a huge part of oncologic robotic surgery was born with the radical prostatectomy.

2.1.1 | Robotic versus open prostatectomy

Despite widespread adoption of the RARP in the 2000s, the first RCT comparing early outcomes following RARP ($n = 157$) versus open radical retropubic prostatectomy (ORP; $n = 151$) was published in 2016. The study compared urinary and sexual function between the two surgical approaches and found similar urinary and sexual function scores at 12 weeks postsurgery and at 24-month follow-up. RARP was associated with less intraoperative bleeding, shorter length of hospital stay (LOS), and a shorter operative time compared to ORP.[12] There was no difference in the rate of positive surgical margins or in evidence of disease progression on imaging between the two cohorts.[12,13] A large-scale, nonrandomized trial from Sweden comparing RARP ($n = 1847$) versus ORP ($n = 778$) had similar findings for urinary function and residual or recurrent disease. However, the authors did note a significant difference in rate of erectile dysfunction in favor of RARP ($p = 0.006$).[14]

In a recent retrospective review comparing RARP to both ORP and laparoscopic radical prostatectomy (LRP), RARP had the lowest odds of experiencing erectile dysfunction, urinary incontinence, or hernia compared with ORP and LRP (all $p < 0.04$). This is one of a few studies to compare the three major approaches and to find both a short-term and long-term functional outcome benefit with the robotic approach.[15]

2.1.2 | Robotic versus laparoscopic prostatectomy

Given the high cost of robotic surgery, understanding the benefits of the robot over other minimally invasive options is important. In 2011, Asimakopoulos et al.[16] published an RCT comparing RARP to LRP and found no significant difference in operative time, estimated blood loss, positive surgical margins, rate of biochemical recurrence, or urinary incontinence. However, there was a significant difference in self-reported capability for intercourse at 12 months in favor of RARP ($p < 0.0001$). The relative risk (RR) of developing severe erectile dysfunction following RARP versus LRP was 0.31, indicating a protective effect of RARP. The authors postulate that this benefit may be due to the increased precision afforded by the robot.[16] This was the first RCT to note an obvious benefit of RARP and these results have been reproduced in another single surgeon RCT.[17]

LAP-01 was the first multi-center RCT comparing RARP ($n = 547$) to LRP ($n = 171$). RARP was associated with higher rates of continence and potency recovery at 3 months with no significant difference in operative time.[18] There was no significant difference in oncologic outcomes at 12 months.[19] Meta-analysis from Ma et al.[20] supports the finding of improved functional outcomes with a robotic approach but again does not reach definitive conclusions regarding oncologic outcomes. The largest body of evidence supporting the use of robotic surgery in cancer comes from RARP for prostate cancer; however, despite the dominance of RARP in the treatment of prostate cancer, current literature does not suggest any benefit in oncologic outcomes over LRP or ORP. One ongoing long-term trial investigating RARP versus ORP will conclude next year and hopefully provide answers.[21]

2.1.3 | Penetrance of robotic prostatectomy

Currently, RARP is the preferred surgical modality for patients with prostate cancer, and it is estimated that 45%–80% of all radical prostatectomies are performed robotically in the United States.[22] Recent National Cancer Database (NCDB) analysis from 2010 to 2017 identified 354 752 patients who underwent radical prostatectomy. 83.9% of these patients underwent RARP, compared with 16.1% ORP. RARP became increasingly more common over the course of the study period, from 75.6% in 2010 to 90.7% in 2017.[23]

Over the last 20 years, a significant portion of urologic oncology has been performed robotically and can serve as a model for surgical oncology. This includes the surgical management of bladder cancer and renal cell carcinoma. RCTs for robot-assisted radical cystectomy and robotic nephrectomy have demonstrated improved short-term outcomes compared to open approaches but no pertinent definitive differences compared to laparoscopy.[24–26] While the literature does not currently suggest an oncologic advantage to RARP, improved functional outcomes, even in the face of equivalent oncologic outcomes, justifies its widespread adoption.

3 | GASTROINTESTINAL SURGERY

Gastric and esophageal cancer are both aggressive malignancies that are frequently found at late stages. Subsequently, 5-year overall survival rates are generally poor. Additionally, both open gastrectomy and esophagectomy are morbid surgeries with a high risk of complications. The option of a minimally invasive approach provides patients with a less morbid option, potentially improving quality of life.

3.1 | Robotic esophagectomy

Minimally invasive laparoscopic (MIE) techniques have improved patients' quality of life after esophagectomy by enabling surgeons to operate through smaller incisions without worse oncologic outcomes.[27,28] However, the traditional laparoscopic approach is not without limitations, including concerns regarding adequate lymph node (LN) dissection, significant heterogeneity in procedure type, and increased risk during the learning period.[29] Recently, the robotic platform has permeated esophageal surgery, both in the abdominal and thoracic approaches, as a possible solution.

3.1.1 | Robotic versus open esophagectomy

The ROBOT trial, a single-center RCT from the Netherlands, has shown an advantage in the robotic versus open approach in esophagectomy for esophageal cancer. Van der Sluis et al. randomized 112 patients to a robot-assisted minimally invasive thoracolaparoscopic esophagectomy (RAMIE) or an open transthoracic esophagectomy (OTE). Overall surgery-related postoperative complications occurred less frequently after RAMIE compared to OTE (RR 0.74, $p = 0.02$). Additionally, RAMIE resulted in a lower rate of overall pulmonary ($p = 0.005$) and cardiac complications ($p = 0.006$) with lower postoperative pain ($p = 0.001$), better short-term quality of life (at discharge $p = 0.02$, at 6-weeks $p = 0.03$), and a better short-term postoperative functional recovery ($p = 0.038$) compared to OTE.[30]

In a propensity score-matched (PSM) analysis evaluating the clinical benefits of RAMIE ($n = 130$) compared to open esophagectomy (OE) ($n = 241$) in squamous cell carcinoma of the esophagus, the RAMIE cohort had a lower incidence of pneumonia ($p = 0.035$), and a lower vasopressor requirement ($p = 0.001$). Regarding long-term outcomes, OE had a significantly higher rate of all-cause mortality ($p = 0.001$) and lower disease-free survival ($p = 0.006$). OE was also associated with more long-term wound-related issues ($p = 0.02$). There was no significant difference in recurrence rates ($p = 0.191$).[31] NCDB review comparing RAMIE to MIE and OE found no significant difference in median survival between the three groups.[32]

Similar advantages of RAMIE have been seen in meta-analyses. Again, RAMIE has been shown to have statistically lower rates of pulmonary complications, including pneumonia, atrial fibrillation, wound infections, shorter LOS, and peri-operative blood loss, compared to OE. However, information regarding long-term oncologic outcomes and survival is limited.[33]

3.1.2 | Robotic versus laparoscopic esophagectomy

The RAMIE Trial was one of the first multi-center RCTs to compare RAMIE to conventional MIE for resectable esophageal squamous cell carcinoma. Early results from this trial show similar rates of conversion, R0 resection, morbidity, and mortality between the two approaches. Notably, RAMIE had a significantly shorter operative time ($p < 0.001$) and higher LN harvest in patients who received neoadjuvant therapy ($p = 0.016$). At the time of publication of this review, long-term results from this trial are still pending.[34] The ROBOT-2 trial is currently underway and will compare RAMIE versus MIE for resectable esophageal cancer.[35]

In a 2010–2016 review of the NCDB comparing RAMIE ($n = 1543$) versus MIE ($n = 5118$), RAMIE had a lower rate of positive margins ($p = 0.001$), higher number of LN evaluated ($p = 0.018$), lower rate of conversion to open ($p < 0.001$) and shorter LOS ($p < 0.001$). On multivariable analysis, conversion rate, margin positivity, and LN harvest remained superior in RAMIE.[36] Single-center retrospective reviews have found similarly improved perioperative outcomes with a robotic approach.[37]

3.1.3 | Penetrance of robotic esophagectomy

The improved perioperative outcomes observed with minimally invasive approaches to esophagectomy have led to increased utilization. Kamarajah et al.[38] reviewed the NCDB database from

2010 to 2017 and identified 11,442 patients who underwent esophagectomy for esophageal cancer; 64% underwent an OE, 27% underwent MIE, and 9% underwent RAMIE. Over the course of the study, RAMIE increased from 3.7% in 2010 to 13% in 2017.[38] Ali et al.[36] investigated the trend of RAMIE among minimally invasive esophagectomies recorded in the NCDB. Of the 6661 minimally invasive esophagectomies performed from 2010 to 2016, 23.2% were RAMIE. Over the study period, RAMIE increased from 10.4% in 2010 to 27.2% of esophagectomies performed minimally invasively in 2016 ($p < 0.001$).[36] As the use of RAMIE increases, long-term outcomes from the RAMIE trial and ROBOT-2 are eagerly awaited.

3.2 | Robotic gastrectomy

Multiple clinical trials have shown that compared to open gastrectomy (OG), a laparoscopic approach decreases postoperative complications while maintaining equivalent oncologic outcomes after resection of gastric cancer.[39–41] Given the convincing evidence for laparoscopic gastrectomy (LG), there have been limited studies comparing robotic gastrectomy (RG) to OG. However, multiple RCTs have been conducted comparing RG to LG.

3.2.1 | Robotic versus open gastrectomy

There is only one RCT comparing RG to OG. Wang et al. randomized 311 patients to RG or OG and found no significant difference in LN dissection or complication rates between the two groups. The RG cohort had less blood loss ($p < 0.001$), shorter LOS ($p = 0.021$), and faster return of bowel function ($p = 0.028$), but was associated with a longer operative time ($p = 0.002$).[42]

The majority of the literature comparing RG to OG is limited to retrospective reviews and meta-analyses. In a PSM analysis of an elderly population (> 70 years old), Garbarino et al. compared 1:1 RG versus OG and found no significant difference in the rate of R0 resection, overall survival (OS), or disease-free survival (DFS). RG had a significantly longer operative time ($p < 0.01$).[43] These findings have been further confirmed by meta-analysis.[44] In one meta-analysis of 11 retrospective studies comparing RG to OG, RG had fewer postoperative complications ($p = 0.025$), less blood loss ($p = 0.001$), and shorter LOS ($p = 0.041$). R0 resection occurred more frequently in the RG group (odds ratio [OR] 6.26).[45]

3.2.2 | Robotic versus laparoscopic gastrectomy

RCTs comparing RG to LG suggest benefits to a robotic approach. Ojima et al.[46] randomized 241 patients to RG or LG and found RG was associated with a lower incidence of postoperative complications compared to LG ($p = 0.02$), but there was no difference in intra-abdominal complications. RG was also associated with significantly longer operative time ($p = 0.001$). In an RCT comparing robotic distal gastrectomy to laparoscopic distal gastrectomy, the robotic cohort was shown to have an improved postoperative course with reduced postoperative morbidity ($p = 0.039$) and a greater number of LNs examined ($p = 0.018$). Long-term outcomes are still pending.[47] Similar findings have been seen in systematic reviews and meta-analyses, thus indicating a potential advantage to RG that warrants further investigation.[48,49]

3.2.3 | Penetrance of robotic gastrectomy

Hirata et al. conducted a NCDB review from 2010 to 2018 for patients who underwent gastrectomy for gastric cancer and identified 22 445 patients: 65% OG, 27% LG, and 8% RG. Over the course of the study period, RG increased from three cases in 2010 to 412 cases (17%) in 2018. While OG remained the predominant approach, the use of LG and RG increased by 11% and 16% respectively, while OG decreased.[50] Literature showing improved short-term outcomes for RG over both OG and LG has been promising. However, with limited long-term data regarding oncologic outcomes, the verdict is still out on RG. Ongoing clinical trials investigating long-term outcomes of RG versus LG will be essential for the further adoption of the robotic gastrectomy.[51,52]

4 | HEPATO-PANCREATO-BILIARY SURGERY

Perhaps the most cautious and debated adoption of robotic surgery has been in complex hepatobiliary and pancreatic oncologic resections. Aside from straightforward liver resections, the implementation of laparoscopy in this field was limited, largely due to the technical challenges and long learning curves. While other operations had demonstrated the safety and feasibility of laparoscopic oncologic resections prior to the introduction of the robot, hepato-pancreatico-biliary (HPB) surgery had not. The rise of robotics within HPB has prompted a simultaneous discussion regarding the oncologic safety of minimally invasive surgery.

4.1 | Robotic pancreatectomy

A pancreatectomy may be performed for a wide range of pancreatic malignancies. Depending on the location of the cancer, either a distal pancreatectomy (DP) or a pancreaticoduodenectomy (PD) is performed in most cases. Although the robotic distal pancreatectomy (RDP) and robotic pancreaticoduodenectomy (RPD) were first described in 2003, the robotic technique is used in a minority of robotic pancreas operations.[53,54] More recently, the RDP and RPD have gradually gained traction.

4.1.1 | Robotic versus open pancreatectomy

In the past 5 years, two RCTs have been conducted investigating outcomes for robotic distal pancreatectomy. The LEOPARD trial, published in 2019, compared minimally invasive distal pancreatectomy (MIDP) with open distal pancreatectomy (ODP). It demonstrated a shorter recovery, less operative blood loss, and less delayed gastric emptying grade B/C in MIDP.[55] More recently, the DIPLOMA trial, an international non-inferiority trial published in 2023, addressed the oncologic safety of MIDP versus ODP. In this study, MIDP had equivalent rates of R0 resection, median LN harvest, and intraperitoneal recurrence. There was no significant difference in survival rate, median time to functional recovery, or LOS.[56] Both studies are limited in the number of RDPs included in the MIDP arm, 11% ($n = 5$) and 27% ($n = 31$), respectively. Still, these are the first RCTs that support earlier retrospective studies in the comparability between RDP and ODP.[57–59] There are two more ongoing RCTs investigating RDP.[60,61]

Currently, no RCTs exist for robotic pancreaticoduodenectomy. However, three trials, DIPLOMA-2, PORTAL, and EUROPA, have recently finished accruing patients, and data comparing RPD to open approach should be available in 2024.[62–64] While RCTs investigating RPD remain ongoing, data from large, retrospective cohort studies have supported the use of the robot for pancreaticoduodenectomy. Multiple studies have found equivalent R0 resection rates between RPD and open pancreaticoduodenectomy (OPD), suggesting one can achieve an adequate oncologic resection robotically.[65,66] An American College of Surgeons (ACS) National Surgical Quality Improvement Program (NSQIP) database analysis of 498 RPDs and 12 612 OPDs showed that patients who underwent RPD were less likely to have any complication ($p = 0.004$) or a surgical complication ($p = 0.008$).[67] This includes a lower rate of clinically relevant postoperative pancreatic fistula (CR-POPF) in RPD, and after PSM, RPD was protective against CR-POPF.[68,69] Majority of studies found similar rates of median survival between RPD and OPD.[57,59] Only one study found a survival advantage with the RPD (HR 0.75, $p = 0.05$).[70]

Multiple meta-analyses have further supported improved perioperative outcomes with the robotic approach. For RDP, data suggests that a robotic approach results in a shorter LOS and decreased operative blood loss compared to an open approach.[71,72] One meta-analysis by Girgis et al.[70] reported a higher mean number of LNs examined in RDP ($p = 0.002$). In this study, RDP was also associated with improved median OS and higher rates of 1-, 3-, and 5-year OS.[70] Similar findings have been seen for RPD. Multiple large meta-analyses have found evidence suggesting that RPD leads to lower operative blood loss, lower wound infection rates and shorter LOS.[73–76]

4.1.2 | Robotic versus laparoscopic pancreatectomy

The use of laparoscopy in pancreatic surgery varies based on procedure. While laparoscopic distal pancreatectomy (LDP) is a popular approach and widely accepted in pancreatic cancer, adoption of the laparoscopic pancreaticoduodenectomy (LPD) has been limited, likely due to the technical difficulty. Currently, there are no randomized trials directly comparing robotic to laparoscopic pancreatectomy.

Accordingly, data is limited to retrospective reviews and meta-analyses. For distal pancreatectomy, RDP is associated with a significantly lower conversion rate compared to LDP.[65,66,77–80] RDP is universally associated with a longer operative time, but with the benefit of higher rates of spleen preservation.[81,82] No statistical differences have been found between RDP and LDP when comparing POPF grade B/C rate, major complications, or blood loss.[83–85] One study showed that RDP has a higher rate of R0 resection.[83] Similarly, for pancreaticoduodenectomy, RPD is associated with a lower rate of conversion than LPD.[86–89] RPD is also associated with significantly less blood loss compared to LPD.[90] In one meta-analysis including 3462 patients (1025 RPD and 2437 LPD), there was no significant difference in postoperative complications, including POPF and mortality, but did note a higher readmission rate in RPD ($p = 0.014$).[91]

4.1.3 | Penetrance of robotic pancreatectomy

Since the introduction of the robotic approach for pancreas surgery, there has been a significant increase in utilization. In one NCBD study from 2010 to 2018, the proportion of RPDs increased from 1% to 7.1%.[92] A similar trend was observed in a nationwide study from the Netherlands, where LPD decreased from 15% to 1%, while RPD increased from 0% to 25%.[93] This isn't to say that RPD has replaced OPD or LPD yet. In a 2017 global survey, 0.22% of pancreatic surgeons reported performing fully RPD.[94] As the utilization of robotic pancreas surgery continues to increase, it is important for patient safety that these procedures occur at high-volume centers. Current guidelines advise that surgeons perform a minimum of 20 RPDs per year to reduce morbidity compared to open PD.[95,96] Furthermore, future studies investigating the long-term oncologic outcomes of robotic pancreas surgery are necessary and should be conducted at high-volume centers.

4.2 | Robotic liver resection

Laparoscopic liver resection has been considered safe and effective for over 15 years, and recent clinical trials comparing laparoscopy to an open approach have supported this sentiment.[97–99] However, the challenges of performing laparoscopic hepatectomies (LH) have led to interest in the use of the robot. Positive outcomes from initial experience with robotic hepatectomy (RH) led to the release of the 2023 International Consensus Guidelines in support of the use of the robot to perform most liver surgeries.[100] Without RCTs comparing robotic liver surgery for primary liver cancer to the open or laparoscopic approach, retrospective studies and meta-analyses shape the current status of robotic liver surgery.

4.2.1 | Robotic versus open hepatectomy

Only one RCT exists comparing robot versus open for simultaneous resection of rectal cancer and liver metastasis. The robotic cohort had a lower rate of complications, but there was no difference in R0 resection rate, 3 year-DFS, or OS. Furthermore, the study primarily focused on the rectal resection, necessitating further RCTs investigating RH.[101] Recent PSM analysis by Rayman et al.[102] of RH ($n = 49$) versus open hepatectomy (OH, $n = 49$) for neoplastic liver disease found that RH had fewer postoperative complications ($p = 0.02$) and a shorter LOS ($p = 0.002$). Furthermore, no differences in long-term survival and oncological safety were found. Most surprisingly, there was no differences seen in cost between OH and RH.[102] In another PSM study from the same group with a specific focus on major liver resections, RH again had a shorter LOS ($p = 0.0001$). There was no significant difference in complications, long-term oncologic outcomes, or OS for the whole cohort. However, patients with hepatocellular carcinoma who underwent robotic resection lived significantly longer ($p = 0.05$).[103]

Meta-analyses also demonstrate improved outcomes with RH. In addition to having lower operative blood loss and shorter LOS, RH is associated with a reduced rate of overall complications.[104–106] Other studies have also confirmed equivalent or reduced overall cost with a robotic approach. While the cost of the surgery is more expensive when performed robotically, the money saved by a shorter hospital stay with less complications offsets the higher perioperative costs.[106–108]

4.2.2 | Robotic versus laparoscopic hepatectomy

Conclusions from retrospective studies and meta-analyses comparing RH to LH are more variable. For perioperative outcomes, RH requires a longer operative time but is consistently associated with a lower conversion rate than LH ($p < 0.001$).[109–112] In most other surgical procedures, a robotic approach is associated with decreased operative blood loss compared to a laparoscopic approach. However, because there is currently no robotic Cavitron® Ultrasonic Surgical Aspirator (CUSA) (Integra LifeSciences, Tullamore, Ireland), RH is mainly performed using the crush clamp technique, thus leading to higher operative blood loss.[109,113,114] There have been no differences seen in quality of oncologic resection, morbidity or mortality between RH and LH across multiple studies.[109–111,113–115] One NSQIP analysis reported higher rate of bile leak in RH during major and right hepatectomies.[116] Unlike in OH, there is no cost benefit for RH over LH.[117]

4.2.3 | Penetrance of robotic hepatectomy

A recent NSQIP analysis from 2014 to 2020 showed that majority of liver resections are still performed open. Of the 21 342 patients included in the analysis: 71% were OH, 25.8% LH, and 3.1% RH. Despite the small portion of cases performed robotically, the authors noted remarkable growth in RH, up to 432% during the study period, particularly among major hepatectomies.[116] Similar trend was seen in NCDB analysis. From 2010 to 2016, Kamel et al. found a significant increase in utilization of RH, from 0.8% to 4.1% ($p < 0.001$). Still, only 2.5% of all hepatectomies, major or minor, were performed robotically.[118]

While early results look promising for the future of RH, there are several limitations to the current literature. First, as previously mentioned, no RCTs for primary liver cancer have been published to date. There is currently one ongoing RCT investigating minimally invasive versus open liver resection for colorectal cancer liver metastases.[119] Systematic reviews and meta-analyses on RH mainly include single-center retrospective studies and case-series, which do not always distinguish between benign and malignant disease, and do not assess long-term prognosis. Additionally, many studies included are over 10 years old, and updated studies are needed. Further development of the necessary robotic instruments (i.e. robotic CUSA) will undoubtably advance the current paradigm for robotic liver resections.

5 | COLORECTAL SURGERY

Early robotic platforms were not designed for multi-quadrant surgery and consequently, their application in colorectal surgery, which often involves working in both the pelvis and splenic flexure, was slow. The release of the da Vinci Xi® (Intuitive Surgical Inc., Sunnyvale, CA) in 2014 made multi-quadrant surgery more feasible, which garnered global interest and spurred adoption of the robotic approach among colorectal surgeons.

5.1 | Robotic versus open colorectal surgery

There is limited prospective data comparing robotic colorectal surgery to an open approach. In a 2015 RCT from India, Somashekhar et al. compared robotic total mesorectal excision (rTME) to open TME (oTME) for rectal cancer and found equivalent oncologic outcomes between the two groups. Furthermore, there was no significant difference in postoperative complications or mortality. rTME had a significantly improved hospital LOS ($p < 0.001$) and estimated blood loss ($p < 0.001$). Operative time was longer in the rTME group but was noted to improve over the course of the trial.[120]

In 2023, Khajeh et al. published a meta-analysis comparing robot-assisted rectal resection to open rectal resection, a total of 1,574 patients from a mix of RCTs and prospective studies were included. The robotic approach was associated with lower estimated blood loss ($p = 0.001$), a longer operative time ($p < 0.00001$), and a shorter LOS ($p = 0.03$). Open resection was associated with a higher rate of surgical site infection compared to the robotic approach without a difference in leak rate. Oncologic resection was superior in the robotic approach, which had a higher rate of R0 resections

($p = 0.04$), negative circumferential resection margin ($p = 0.03$), and number of LN examined ($p = 0.02$); however, there was no difference in DFS or OS.[121]

5.1.1 | Robotic versus laparoscopic colorectal surgery

Colon cancer

One RCT has compared robotic colectomy (RC) to laparoscopic colectomy (LC) for right sided colon cancer. In this trial from South Korea, there was no significant difference in 5-year DFS or OS between the two cohorts. RC was associated with a longer operative time ($p < 0.001$) and higher cost ($p = 0.013$).[122]

In a large ACS-NSQIP analysis from 2015 to 2020 of over 50 000 patients with colon cancer who underwent either RC or LC, primary outcome was "textbook outcome" which was defined as the absence of 30-day complications, readmission, or mortality, and LOS < 5 days. RC was associated with a higher rate of "textbook outcome" than LC ($p < 0.001$). RC was also associated with longer operative time ($p < 0.001$), higher number of LNs examined ($p < 0.001$), and lower conversion rate ($p < 0.001$). There was no significant difference in overall morbidity or mortality.[123] Similar findings have been seen in a Danish database review.[124] Meta-analyses generally support the findings seen in retrospective reviews and database studies.[125,126] Overall, RC is associated with shorter LOS, lower conversion rate, higher number of LN examined, and longer operative time, without impact on overall morbidity or mortality compared to LC.

5.1.2 | Rectal cancer

The adoption of robotic surgery for low anterior resections, abdominoperineal resections, and TME in rectal cancer has been more rapid than for colon cancer. Multiple large-scale RCTs have been conducted comparing a robotic and laparoscopic approach. The ROLARR trial randomized 471 patients with rectal cancer to a robotic or laparoscopic surgery. The primary outcome measure was the rate of conversion to open surgery, which was not significantly different based on approach. There was also no significant difference in rate of margin positivity between the two cohorts. The authors concluded that a robotic approach did not provide an advantage in rectal cancer resection.[127] Alternatively, the REAL trial published in 2022 is the largest RCT comparing robotic TME (rTME) to laparoscopic TME (laTME) for resectable rectal adenocarcinoma. rTME was associated with lower rate of positive resection margin ($p = 0.023$), higher rate of macroscopic complete resection ($p = 0.042$), lower conversion rate ($p = 0.021$), less postoperative complications ($p = 0.003$), and shorter LOS ($p = 0.0001$). This was the first RCT to report an advantage to rTME over laTME.[128]

The transanal total mesorectal excision (taTME) has recently emerged as another minimally invasive technique to remove low-rectal cancers. Short-term outcomes have demonstrated taTME is safe and feasible, when performed by experienced surgeons.[129] Long-term outcomes are still under investigation after a moratorium was placed on taTME in Norway due to observed high recurrence rates.[130] Early data comparing the taTME to rTME does not find significant difference in short-term outcomes, but higher level evidence is needed.[131,132] While there are no current RCTs comparing the two approaches, the planned ROTA trial will investigate 3-year DFS.[133]

5.1.3 | Penetrance of robotic colorectal surgery

Parascandola et al. reviewed the NCDB from 2010 to 2016 and identified 50 855 patients diagnosed with rectal adenocarcinoma who underwent surgery. During that time, 15.6% were performed robotically, 33% laparoscopic, and 51.4% open. Over the course of the study, the utilization of MIS significantly increased, while the utilization of an open approach decreased ($p < 0.0001$).[134] Another NCDB study found that from 2008 to 2019, open rectal surgery decreased from 60.1% to 30.1%, while robotic rectal surgery increased from 5.2% to 28.4%.[135] While majority of colorectal surgery today is performed laparoscopically, the dramatic increase in robotic rectal surgery will likely continue.

6 | ENDOCRINE SURGERY

The development of robotic endocrine surgery, specifically the robotic thyroidectomy which was first performed in 2009, revolutionized what people thought possible with the robot.[136] Although accepted in a body cavity or at an orifice, subcutaneous surgery initially seemed to be an exception to the robotic approach. However, the robotic thyroidectomy (RT) defied this logic and allowed for a "scarless" thyroidectomy providing superior cosmetic results for patients, and includes an axillary approach, an anterior/breast approach, a retro-auricular approach, or a transoral approach.[137]

6.1 | Robotic versus open thyroidectomy

Currently, there are no published randomized controlled trials comparing the robotic and open approach for thyroidectomy. The largest retrospective review of 3000 South Korean patients who underwent robotic trans-axillary thyroidectomy demonstrated that when performed by experienced surgeons, this procedure is a safe and effective treatment of thyroid cancer.[138] In the largest US cohort study from Johns Hopkins, 216 RTs were performed and demonstrated comparable outcomes with the traditional transcervical approach.[139]

In a systematic review and meta-analysis investigating the outcomes of the gasless trans-axillary approach, the bilateral axillo-breast approach, and the transoral approach as compared to the open approach, the minimally invasive approaches appeared to be safe and feasible in thyroid cancer.[140] The traditional open approach had the shortest operative time and retrieved more LNs than RT, but there was no difference in transient hypocalcemia, recurrent laryngeal nerve palsy, or bleeding between approaches. Unsurprisingly, RT was associated with higher cosmetic satisfaction. These results have been replicated in other meta-analyses on the topic.[141,142]

6.1.1 | Robotic versus endoscopic/laparoscopic thyroidectomy

Transoral thyroidectomy has increasingly become the favored remote access approach for RT given the less extensive flap dissection. This procedure can be performed endoscopically via the transoral endoscopic thyroidectomy vestibular approach (TOETVA) or robotically via the transoral robotic thyroidectomy (TORT). Both procedures start with an intra-oral incision in the lower lip, and dissection is carried down to the neck. For TOETVA, a 10 mm port is placed in this developed space, and two 5 mm ports are placed laterally on either side through two stab incisions. A 30° 10 mm laparoscope is placed in the center port for visualization; cautery, an ultrasonic device, and suction-irrigation alternate through the two additional ports.[143] For TORT, the subplatysmal plane is developed before docking the robot.[144] The robot allows for improved visualization and the use of articulated instruments but requires an additional axillary incision for retraction.[145] Because TOETVA doesn't require robotic docking, it is generally a shorter and less expensive operation. Both TORT and TOETVA have been shown to be safe options when compared to the conventional open thyroidectomy.[143,146] In a meta-analysis comparing the two approaches, TOETVA was associated with a shorter operative time and a higher rate of transient recurrent laryngeal nerve palsy, but there was no significant difference in LN harvest, postoperative pain, LOS, or other postoperative complications.[147] There remains a need for large scale trials comparing the two approaches to see if improved visualization with the robot provides any advantage to TORT.

6.1.2 | Penetrance of robotic thyroidectomy

The utilization of the robot to perform thyroid surgery varies worldwide. In South Korea, where this technique was developed, based on published case studies from 2005 to 2014, the use of robotic surgery for thyroidectomy was as high as 14%.[148] Alternatively, in a review of the NCDB from 2010 to 2016, of the 217 938 patients who underwent thyroid surgery, only 0.34% had robotic thyroid surgery, while 3378 (1.55%) received endoscopic surgery.[149] Notably, these results likely do not include the transoral approach, as the first successful performance of TORT in humans was not published until 2015.[150]

7 | BREAST SURGERY

Breast surgery has evolved significantly since the modified radical mastectomy of the Halsted era. With the introduction of the robotic nipple sparing mastectomy (rNSM), there now exists a way for patients to maintain the outward appearance of the breast via small surgical incision, without compromising oncologic outcomes. The rNSM was first described in Italy in 2015, and is achieved through a small incision in the axilla, by which a single port is introduced and allows for the use of three to four instruments, including a high definition camera for improved visualization.[151]

7.1 | Robotic versus open mastectomy

There are very limited number of RCTs comparing rNSM to an open approach. Toesca et al. published the first RCT in 2022 and while the rNSM was associated with longer operative time, there was no significant difference in complications. Patient satisfaction with cosmesis, psychosocial, physical, and sexually well-being was significantly higher in the robotic cohort. At median follow-up, no events of local recurrence were observed in the open or robotic population.[152] As evident in Figure 1, the tissue transillumination during the robotic approach can help the surgeon to identify the margins of the breast (Figure 1). At median follow-up, no events of local recurrence were observed in the open or robotic population.[152] There are currently multiple ongoing multi-institutional RCTs both in the US and internationally, that aim to further investigate the safety and effectiveness of rNSM.

In an international, multicenter pooled analysis of 659 women with early breast cancer or BRCA mutations who underwent rNSM, the robotic cohort was found to have lower rates of complications and nipple necrosis compared to an open approach, without significant difference in oncologic outcomes.[153] A recent meta-analysis of rNSM versus conventional, open approach, found similar results, including equivalent rates of recurrence and rate of positive margins.[154] Despite these promising results, there remains key concerns regarding rNSM including increased cost, long-term oncologic outcomes, level of experience and skill, and standardization of training.[155]

7.1.1 | Robotic versus endoscopic/laparoscopic mastectomy

Endoscopic nipple-sparing mastectomy (eNSM), which is performed using a laparoscope and small axillary and peri-areolar incisions was first described in 2001, and shown to be safe for patients with breast cancer.[156–158] While eNSM has been performed successfully in Asian countries, it never gained favor in most Western countries, including the United States.[159] One non-randomized trial exists comparing rNSM and eNSM, and found no difference in oncologic outcomes or

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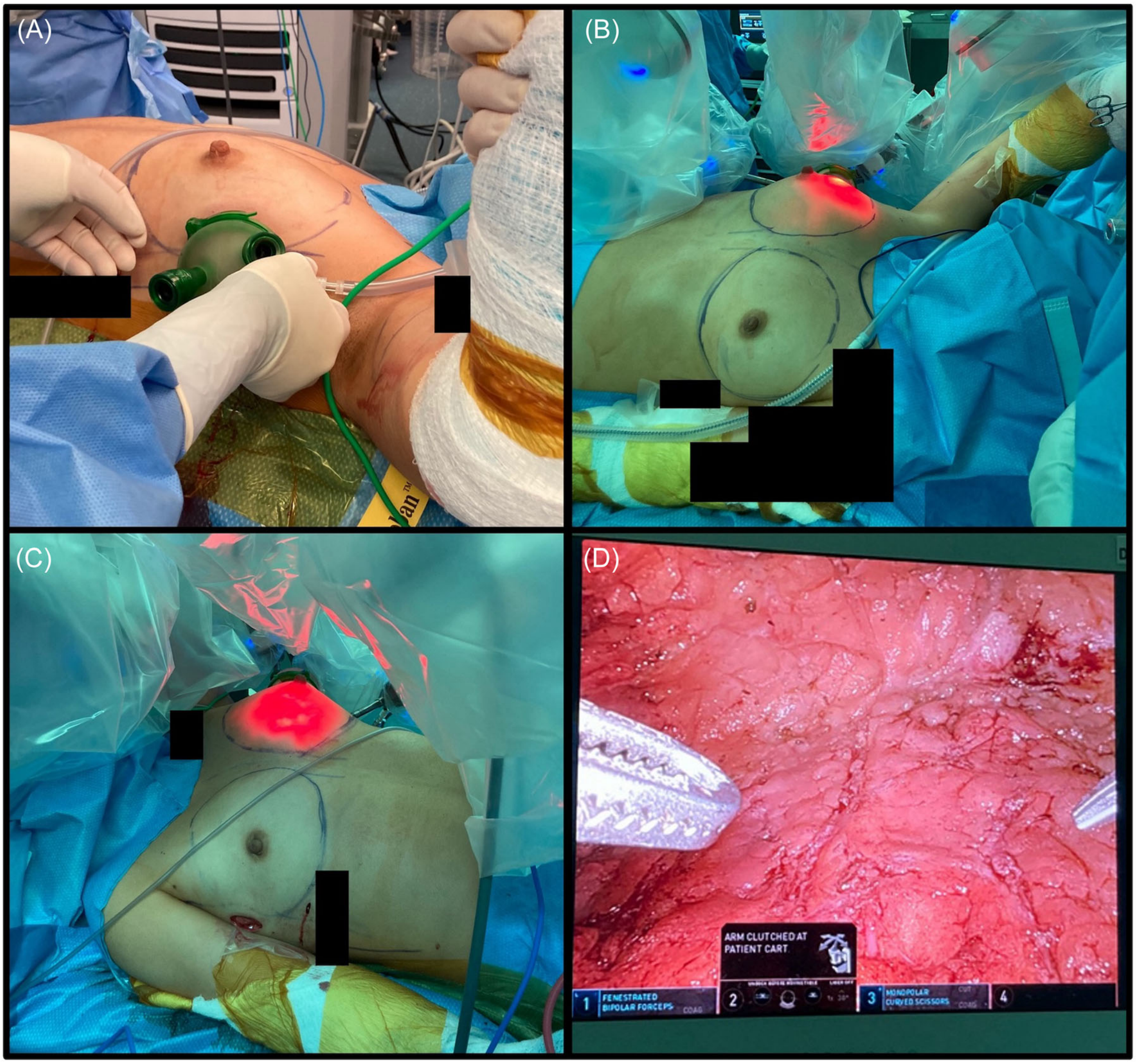

FIGURE 1 Bilateral robotic nipple-sparing mastectomy (rNSM). (A) Port placement before docking robot. (B) rNSM of right breast. (C) rNSM of right breast completed, rNSM of left breast in process, transillumination of breast margins. (D) Intracorporeal view from robotic camera during rNSM.

postoperative complications. eNSM was associated with a longer operative time but lower cost.[160]

7.1.2 | Penetrance of robotic mastectomy

The introduction of the rNSM has not been without controversy. In 2019, due to growing interest in rNSM despite limited level one evidence in support of the procedure, the US Food and Drug Administration (FDA) issued a statement warning against the use of robotic assisted surgical devices in mastectomy and other cancer related surgeries.[161] Those in support of the rNSM developed the first consensus statement on robotic mastectomy in 2020 to promote best practices.[162] A second warning against robotic mastectomy was again released by the FDA in 2021.[163] Given these warnings, majority of rNSMs in the US are currently being performed on clinical trial, thus limiting current data on the utilization of rNSM. There are multiple ongoing clinical trials, both in the United States and abroad, investigating the role of rNSM compared to endoscopic and conventional approaches that will hopefully provide answers in the coming years.[164–167]

8 | GYNECOLOGIC ONCOLOGY

This review has come full circle back to the pelvis. Along with urologists, gynecologic surgeons were among the earliest adopters of the robotic platform in the early 2000s. Data from experience with endometrial and cervical cancer highlight the advantages and the potential challenges of adapting robotic techniques for oncologic surgery.

TABLE 1 Summary of current randomized controlled trials.

Author	Year	Organ	Comparison	Operative time	Estimated blood loss	Conversion rate	Margin positivity	Lymph node yield	Length of stay	Cost	Morbidity	Functional recovery	Disease free survival	Overall survival
Yaxley et al.	2016	Prostate	Open vs. robotic	R	R	N/A	=	R	R	N/A	=	=	N/A	N/A
Coughlin et al.	2018	Prostate	Open vs. robotic	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	=	N/A	N/A
Stolzenburg et al.	2021	Prostate	Laparoscopic vs. robotic	=	L	=	=	=	N/A	N/A	=	R	N/A	N/A
van der Sluis et al.	2019	Esophagus	Open vs. robotic	O	R	N/A	=	=	=	N/A	R	R	=	=
Yang et al.	2022	Esophagus	Laparoscopic vs. robotic	R	=	=	=	R in neo-adjuvant, = for all LN	=	N/A	=	P	P	P
Wang et al.	2016	Stomach	Open vs. robotic	O	R	N/A	=	=	R	N/A	=	N/A	N/A	N/A
Ojima et al.	2021	Stomach	Laparoscopic vs. robotic	L	=	=	=	=	=	N/A	R	P	P	P
de Rooij et al.	2019	Pancreas	Open vs. laparoscopic/robotic	O	M	N/A	=	=	M	=	=	M	N/A	N/A
Korrel et al.	2023	Pancreas	Open vs. laparoscopic/robotic	O	=	N/A	=	=	=	=	=	=	=	=
Chang et al.	2023	Liver	Open vs. robotic	O	R	N/A	=	N/A	R	O	R	R	=	=
Park et al.	2019	Colon	Laparoscopic vs. robotic	L	=	=	N/A	=	=	L	=	N/A	=	=
Somashekhar et al.	2015	Rectum	Open vs. robotic	O	R	N/A	=	=	R	N/A	=	=	N/A	N/A
Jayne et al.	2017	Rectum	Laparoscopic vs. robotic	L	N/A	=	=	=	=	L	=	=	P	P
Feng et al.	2022	Rectum	Laparoscopic vs. robotic	=	R	R	R	R	R	L	R	P	P	P
An et al.	2022	Breast	Open vs. robotic	O	=	N/A	=	N/A	N/A	N/A	=	=	P	P
Mäenpää et al.	2016	Endometrium	Laparoscopic vs. robotic	R	=	R	N/A	=	=	N/A	=	N/A	N/A	N/A
Ramirez et al.	2018	Cervix	Open vs. laparoscopic/robotic	N/A	N/A	N/A	=	=	M	=	O	N/A	O	O

Abbreviations: "=", equivalent; L, favors laparoscopic; LN, lymph node; M, favors minimally invasive; O, favors open; P, pending; R, favors robot.

8.1 | Endometrial cancer

In 2009, the Gynecologic Oncology Group reported the results of the randomized LAP2 Study comparing laparoscopic staging to open for patients with Stage I and II endometrial cancer, which demonstrated improved postoperative outcomes with no significant difference in disease recurrence or OS.[168,169] This data was supported by the multinational, randomized laparoscopic approach to cancer of the endometrium (LACE) trial confirming minimally invasive surgery as the standard of care in early endometrial cancer.[170,171]

8.1.1 | Robotic versus laparoscopic versus open surgery for endometrial cancer

There is limited prospective data directly comparing robotic, laparoscopic, and open surgery for endometrial cancer. Mäenpää et al. randomized 101 patients with endometrial cancer to robotic assisted or traditional laparoscopic staging. Compared to traditional laparoscopy, the robotic cohort had shorter operative time ($p < 0.001$) and decreased conversion to open ($p = 0.02$). There was no difference in LN harvest, bleeding, hospital LOS, or postoperative complications.[172] Ran et al. published a meta-analysis of 22 studies including 4420 patients in 2014. The robotic approach was equivalent to laparoscopy in terms of operative time, hospital LOS, and number of complications but showed benefits in reduced blood loss and lower rates of conversion to laparotomy.[173] A 2019 Danish study examined the impact of national introduction of robotic surgery for endometrial cancer utilizing a prospective national registry. The authors found that adoption of robotic surgery was widespread, totaling 50% of surgeries following introduction. Following robotic introduction, open surgery was associated with increased odds of severe complication or death on adjusted analysis (OR 3.87). There was no difference when laparoscopic was compared to a robotic approach (OR 1.50).[174]

8.1.2 | Penetrance of robotic surgery for endometrial cancer

Since the publication of landmark laparoscopy trials, increasing adoption of minimally invasive approaches mirrored increased utilization of robotic surgery for endometrial cancer. In an analysis of trends in minimally invasive surgery in the United States using the Premier Healthcare Database, Casarin et al. found that from 2008 to 2015 the proportion of minimally invasive surgery for endometrial cancer rose from 28% to 71%. This increase was driven by increasing adoption of robotic surgery, from 9% in 2008 to 57% in 2015.[175] Current data suggest minimally invasive surgery improves perioperative outcomes without sacrificing oncologic outcomes. Robotic surgery may offer improvements in conversion rate which could

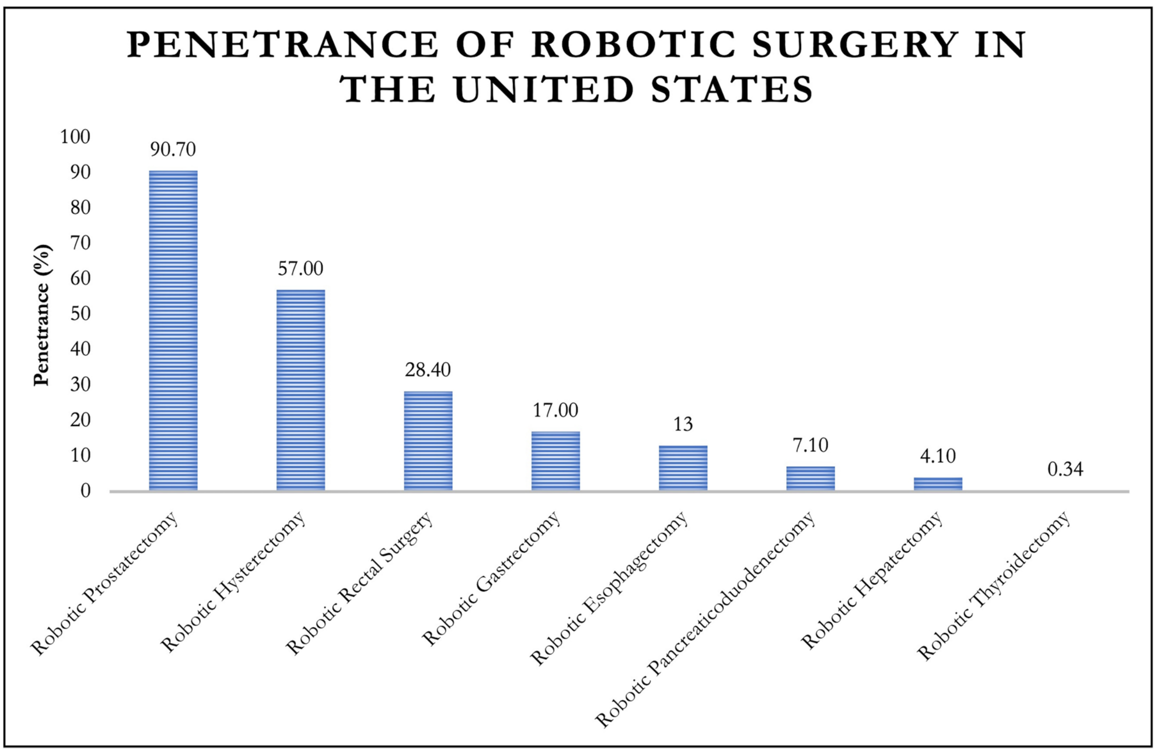

FIGURE 2 Current penetrance of robotic surgery in the United States by procedure. Data referenced throughout paper, primarily NCDB or NSQIP studies from 2008 to 2020.

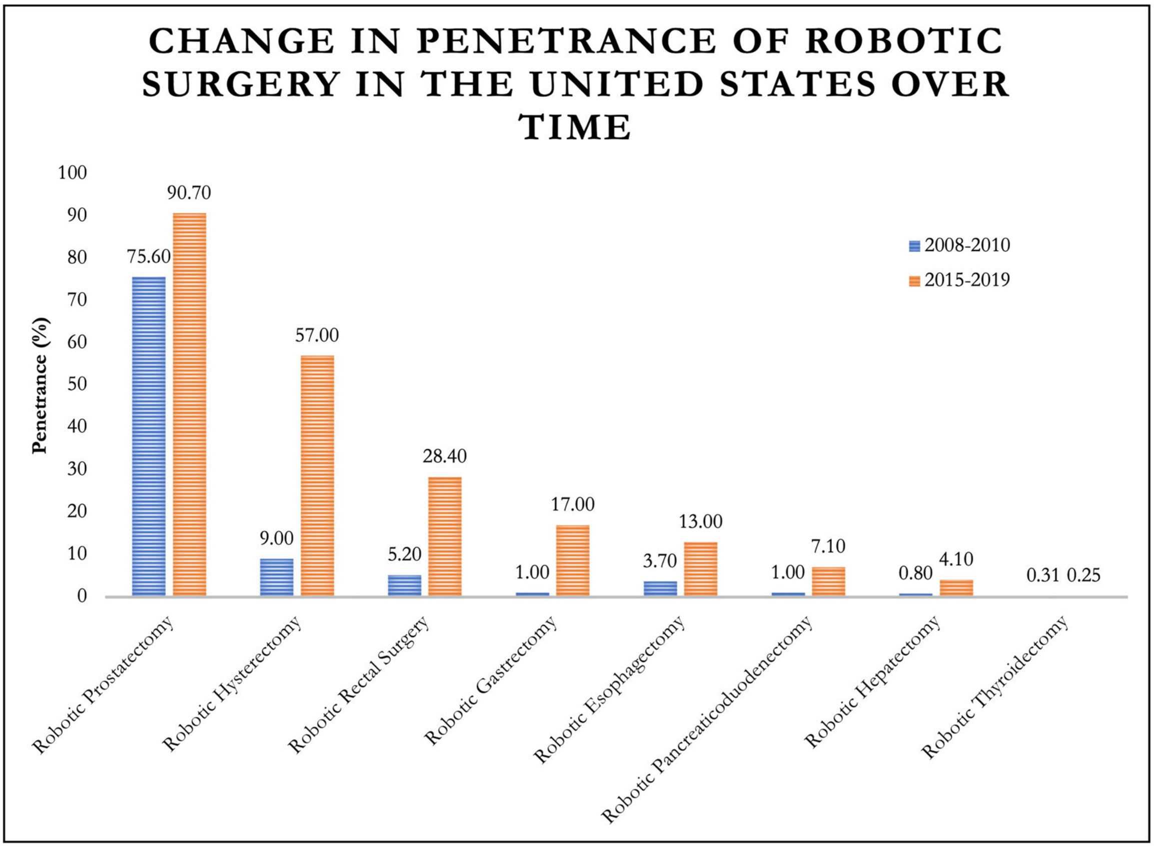

FIGURE 3 Change in penetrance of robotic surgery in the United States over the last decade, by procedure. Data referenced throughout paper, primarily NCDB or NSQIP studies from 2008 to 2020.

impact additional outcomes of interest. High-quality data is needed to elucidate the potential advantages of a robotic over laparoscopic approach for endometrial cancer.

8.2 | Cervical cancer

After FDA approval was granted for gynecologic cancers in 2005, robotic approaches for early-stage cervical cancer were quickly adopted.

8.2.1 | Robotic versus open surgery for cervical cancer

In 2018, results of the laparoscopic approach to cervical cancer (LACC) trial called into question the oncologic safety of minimally invasive approaches to early cervical cancer. Ramirez et al.[176] randomized patients with stage IA1, IA2, and IB1 cervical cancer to minimally invasive (laparoscopic or robotic) or open surgery. Minimally invasive surgery was associated with decreased DFS (HR 3.74) and OS (HR 6.00). A simultaneously published retrospective cohort study conducted by Melamed et al.[177] analyzed outcomes of patients with IA2 or IB1 cervical cancer who underwent open or minimally invasive surgery in the national Surveillance, Epidemiology, and End Results (SEER) database. Similar to findings by Ramirez et al.,[176] this retrospective analysis demonstrated minimally invasive radical hysterectomy was associated with worse 4-year mortality compared to an open approach ($p = 0.002$).[177]

While no definitive explanation for the survival differences in the LACC trial have been shown, multiple explanations have been proposed including the utilization of cervical manipulators, level of training, and issues with standardization of surgical technique. Additionally, as the robotic approach only accounted for 16% of minimally invasive surgeries in the analyzed cohort, the generalizability of findings to robotic surgery remains unclear. Several ongoing trials aim to address questions posed by the LACC trial. The robot-assisted approach to cervical cancer (RACC) trial is an ongoing international multi-center, randomized controlled trial comparing 5-year recurrence free survival of robotic to open radical hysterectomy for early-stage cervical cancer.[178] The ROCC trial (robotic vs. open hysterectomy surgery in cervix cancer) is similarly comparing robotic to open radical hysterectomy with the addition of tumor containment before colpotomy.[179] Data from these studies will help address the safety and suitability of robotic approaches to cervical cancer.

Introduction of the robotic platform transformed the landscape of gynecologic surgery. While immediate benefits of robotic surgery including improved perioperative outcomes, complications, and LOS

TABLE 2 Summary of fields lacking randomized controlled trials and ongoing trials.

Organ	Lacking randomized control trial	Ongoing randomized control trials
Prostate	–	• **PROSTQA-RP2:** Effectiveness of open and robotic prostatectomy
Esophagus	–	• **ROBOT-2:** RAMIE versus MIE for resectable esophageal cancer, a randomized controlled trial
Stomach	–	• **MONA LISA:** Randomized controlled phase III trial to investigate superiority of robot-assisted gastrectomy over laparoscopic gastrectomy for clinical stage T1-4aN0-3 gastric cancer patients • **CLASS14:** A multicenter, RCT study of the clinical efficacy of robotic and laparoscopic gastrectomy in neoadjuvant gastric cancer
Pancreas	• Open vs robotic pancreaticoduodenectomy • Laparoscopic vs. robotic distal pancreatectomy • Laparoscopic vs. robotic pancreaticoduodenectomy	• **DISPACT-2:** A randomized controlled trial to compare postoperative complications between minimally invasive and open DIStal PAnCreaTectomy • **MIRROR:** The therapeutic evaluation of minimal invasive radical antegrade modular pancreatosplenectomy for left-sided pancreatic cancer patients • **DIPLOMA-2:** Minimally invasive versus open pancreatoduodenectomy for pancreatic and periampullary neoplasm • **PORTAL:** Robotic versus open pancreatoduodenectomy for pancreatic and periampullary tumors • **EUROPA:** Evaluation of robotic versus open partial pancreatoduodenectomy
Liver	• Open vs. robotic hepatectomy (primary liver/primary focus on liver surgery related outcomes) • Laparoscopic vs. robotic hepatectomy	• Minimally invasive versus open liver resection for patients with colorectal cancer liver metastases
Colon	• Open vs. robotic colectomy	–
Rectum	–	• **ROTA:** Robotic versus TaTME rectal surgery
Thyroid	• Open vs. robotic thyroidectomy • Transoral endoscopic thyroidectomy vestibular approach vs robotic thyroidectomy	–
Breast	• Endoscopic vs. robotic nipple sparing mastectomy	• Safety and feasibility of robotic SP nipple sparing mastectomy • Robotic versus open NSM for early stage breast cancer (SP NSM) • Robotic assisted da Vinci Xi prophylactic nipple sparing mastectomy • Robotic nipple-sparing mastectomy versus conventional open technique
Gynecology	–	• **RACC:** Robotic-assisted approach to cervical cancer • **ROCC:** A trial of robotic versus open hysterectomy surgery in cervix cancer

were easily appreciated, the potential oncologic disadvantages shown in cervical cancer highlight the need to tailor the approach for every individual patient and oncologic scenario.

9 | CONCLUSION

With the publication of the LACC trial in 2018 detailing decreased DFS and OS with minimally invasive surgery for cervical cancer, the field of robotic surgical oncology collectively held its breath. This was the first RCT that demonstrated significantly worse long-term outcomes with a robotic approach (Table 1). Furthermore, this trial was published at a time when the use of robotic surgery was increasing in surgical oncology. In response, the FDA released warnings against the use of the robot in cancer surgery, citing limited level one evidence supporting equivalent safety to laparoscopic and open approaches. Critics of the robot argued that despite the dramatic increase in utilization of robotic surgery, existing clinical trials failed to show a significant benefit to offset the increased cost, and now, demonstrated harm. The reasons behind the negative results of the LACC trial remain unclear, with many in the field placing blame on the cervical manipulator which is not used in open surgery. Ongoing trials will hopefully provide better answers.

Other randomized trials, PSM and meta-analyses across surgical oncology have demonstrated that robotic surgery can be a safe alternative to open and laparoscopic surgery. While long-term outcomes are still highly anticipated, short-term outcomes have demonstrated that robotic surgery is almost unanimously associated with equivalent to improved peri-operative outcomes, and in some cases, improved morbidity. High cost and long operative time are two current limitations of robotic surgery. However, in robotic prostatectomy, the procedure in which surgeons have the most experience operating robotically, shorter operative times were observed with a robotic approach compared to even an open approach. As surgeons gain more experience operating robotically, postoperative outcomes, including operative time, will likely only continue to improve.[180] Since urology and gynecology were early adopters of the technique, the penetrance of robotic surgery in these fields has been much more dramatic than in general surgery (Figure 2). However, based on the observed trends over the last decade, it is possible that other areas of surgical oncology can reach such levels in the future, some sooner than others (Figure 3). Furthermore, unlike in the current studies where trailblazers were developing these technical skills while in clinical practice, surgeons are now learning robotic skills as residents and preferring the robotic platform early in their careers.[181,182] Decrease in both postoperative complications and hospital length of stay will hopefully offset the higher operative cost of robotic surgery, as is seen with robotic hepatectomy. Furthermore, as market competition increases within robotic technology, costs will continue to decrease.

The question of what is needed to support robotic surgery, noninferiority versus superiority, is heavily debated. The other main question is what metric must be proven. The staunchest robotic critics will be appeased only by improved overall survival and every other outcome will be judged as trivial. However, recalling Dr. Cady's sage advice "Biology is King and Selection is Queen," no one would expect to answer this question with discussions of technique. Dr. Bernard Fischer even proved this principle to Dr. Halsted in several RCTs. The next decade of robotic surgery will be an exciting one. With large scale clinical trials in nearly every aspect of robotic surgical oncology currently ongoing, we will likely learn the fate of the robot in certain fields (Table 2). Due to the development of robotic training curricula, the next generation of surgical oncologist, those to whom the robot is a key tool in their arsenal, will enter the beginning of their careers with experience operating robotically. This will only further improve patient outcomes. It is undoubtably an exciting time to be a surgical oncologist.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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