ARTICLE TITLE: The Current Status of Robotic Oncologic Surgery

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The Current Status of Robotic Oncologic Surgery

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The use of robotic assistance facilitates minimally invasive surgery and has been widely adopted across multiple specialties. This article reviews the published literature on use of this technology for treatment of oncologic conditions. PubMed searches were performed for articles published between 2000 and 2012 using the keywords “robotic” or “robotic surgery” in conjunction with “oncology” or “cancer.” Although the most common use for robotics was to treat urologic oncologic conditions, it has also been widely adopted for gynecologic, general, thoracic, and head and neck surgeries. For several procedures, there is evidence that robotics offers short-term benefits such as shorter lengths of stay and lower intraoperative blood loss, with safety profiles and oncologic outcomes comparable to open or conventional laparoscopic approaches. However, long-term oncologic outcomes are generally lacking, and robotic surgeries are more costly than open or laparoscopic surgeries. Robotic technology is widely used in oncologic surgery with demonstrated short-term advantages. However, whether the benefits of robotics justify the higher costs warrant large comparative effectiveness studies with long-term outcomes.

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Introduction

The use of robotic assistance during minimally invasive surgery was first described in 1985, and the technology has evolved to its current state in the form of the da Vinci surgical system (Intuitive Surgical, Sunnyvale, Calif). Following receipt of US Food and Drug Administration approval in 2000 for adult and pediatric surgeries, it has been widely adopted and is currently the sole commercially available robotic surgical unit.

The technology offers advantages of a 3-dimensional view of the operative field, absence of a fulcrum effect, 7 versus 4 degrees of freedom of movement compared with conventional laparoscopy, with “wristed” instruments that facilitate intracorporeal suturing, elimination of surgeon tremor, and ergonomic benefits. Thus, robotic assistance purportedly facilitates the learning curve for open surgeons transitioning to minimally invasive surgery,1-3 and has consistently reproducible advantages over open approaches, including smaller incisions, reduced intraoperative blood loss, decreased postoperative pain, and shorter hospital lengths of stay (LOS) and convalescence.3-5 Disadvantages of robotic-assisted surgery include the absence of tactile feedback and instrument collisions when traversing wide surgical fields.

Although the da Vinci system was originally intended for cardiac surgeries, it has found widespread applications across multiple specialties, with the vast majority of cases dedicated toward oncologic procedures. We review the outcomes from the common applications of robotic technology in cancer therapy.

Methods

We performed PubMed searches for English language articles published between 2000 and 2012 using the keywords “robotic” or “robotic surgery” in conjunction with “oncology” or “cancer.” Based on these criteria, we identified the most commonly performed robotic procedures for oncologic conditions.

For urologic procedures, these included radical prostatectomy for prostate cancer, radical cystectomy for bladder cancer, and partial nephrectomy for renal masses. In gynecology, robotics was used for radical hysterectomy for endometrial, cervical, and ovarian cancers. In head and neck surgery, these included transoral surgery for oropharyngeal lesions and thyroidectomy for thyroid cancer.

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In general surgery, robotic-assisted surgery is used for resections for colon and rectal cancers, pancreatectomy for pancreatic cancer, adrenalectomy for adrenal lesions, heptectomy for liver lesions, and gastrectomy for stomach cancer. In thoracic surgery, robotic-assisted surgery is used for lobectomy for lung lesions and esophagectomy for esophageal cancer.

We refined our search by using the keywords “robotic” or “robotic surgery” in conjunction with the name of the above procedures or associated malignancies. There was significant variation in procedure-specific robotic experiences. For instance, there was a greater concentration of experiences with prostate and endometrial cancers, whereas experiences with renal, bladder, cervical, thyroid, adrenal, colorectal, and lung cancers were less common. In addition, robotic experiences were rare with oropharyngeal, pancreatic, hepatic, esophageal, and gastric malignancies. Due to the scope of this review, we excluded studies with low case numbers, such as case reports. We reviewed original studies, systematic reviews, and meta-analyses. For procedures where no such studies exist, we present the largest and highest quality studies.

**Results**

**Radical Prostatectomy**

Robotic-assisted laparoscopic radical prostatectomy (RALP) for prostate cancer is by far the most commonly performed robotic operation, and exceeds use of laparoscopic and open radical prostatectomy.\(^6\) Given the high cancer-specific survival following radical prostatectomy, there is significant emphasis on preservation of urinary and sexual function.

Tewari et al performed a comparative meta-analysis of 167,184 open, 57,303 laparoscopic, and 62,389 RALP procedures, using propensity adjustment to control for age, prostate-specific antigen, and pathologic characteristics.\(^7\) Nine of the 400 studies directly compared all 3 surgical approaches. After adjustment, RALP was associated with lower estimated blood loss (EBL) than open and laparoscopic approaches (-562.5 mL [95% confidence interval (CI) = -485.2, -639.8] and -127.8 mL [95% CI = -95.4, -160.2]; both P < .0001) and fewer blood transfusions than open approaches (-18.1% [95% CI = -14.6, -21.6]; P < .0001). However, transfusions were similar for RALP versus laparoscopy. RALP LOS in the US was 1.69 days (95% CI = 1.5, 1.9) and 0.78 days (95% CI = 0.5, 0.9) shorter than open and laparoscopic approaches, respectively (both P < .0001). Internationally, RALP LOS were 3.65 (95% CI = 2.8, 3.5; P < .001) and 1.04 (95% CI = 0.3, 1.5; P = .005) days shorter than open and laparoscopic approaches. The frequency of open conversions did not vary between RALP and laparoscopic radical prostatectomy. Although perioperative mortality did not differ, RALP had lower incidences of readmissions, reoperations, nerve injury, rectal injury and fistulae, deep vein thromboses, and sepsis compared with laparoscopy (all P ≤ .003). Compared with open radical prostatectomy, RALP had fewer readmissions, ureteral injuries, deep vein thromboses, hematomas, lymphoceles, anastomotic leaks, and wound infections (all P ≤ .012). However, bowel injuries were more frequent with RALP versus open radical prostatectomy (P = .03). In addition, the likelihood of reoperation, vessel, nerve, bladder, and rectal injuries, as well as ileus were comparable for robotic versus open approaches. After adjustment, there were fewer positive surgical margins for T2 disease with RALP versus laparoscopic radical prostatectomy (10.7% vs 13.0%; P = .01). Moreover, margin positivity was similar for other stages and also when comparing robotic-assisted versus open radical prostatectomy. However, comorbidity was not controlled for, and while there were small but significant differences in the likelihood of certain complications, the clinical significance is unclear.

Comparison of urinary and sexual function recovery is obfuscated by varying definitions, absence of longer follow-up, and low response rates. Ficarra et al performed a systematic review and found 12 surgical series (5 robotic) ranging from 105 to 1577 subjects that report biochemical disease-free survival, continence, and potency outcomes, none of which were direct comparisons.\(^8\) Robotic-assisted versus open radical prostatectomy continence (requiring a safety pad or no pad) ranged from 80% to 98% versus 93.3% to 95%. Potency sufficient for intercourse with or without medications was 60% to 96.6% versus 62% to 81.3% for robotic-assisted versus open radical prostatectomy. Biochemical disease-free survival for robotic-assisted versus open radical prostatectomy was 88% to 98% versus 78.7% to 96.4%, respectively. However, follow-up lengths varied, ranging from 12 to 48 months, and no statistical comparisons were performed. Menon et al\(^9\) reported on 1384 RALP cases with median 5-year follow-up with results that were similar to large open series.\(^10-13\)

These outcomes from high-volume surgeons may not be generalizable, because 33.1% of robotic-assisted radical prostatectomy procedures are not performed at academic centers.\(^14\) However, a survey of random Medicare beneficiaries comprising 406 robotic-assisted versus 220 open radical prostatectomy found no difference in perception of problematic urinary or sexual function.\(^15\) A US population-based study found that after propensity adjustment for demographics and comorbidities, without tumor characteristics, robotic assistance versus open radical prostatectomy was associated with fewer transfusions (P < .001), fewer intraoperative and postoperative complications (all P < .024), and lower likelihood of prolonged LOS (P < .001).\(^6\) However, inpatient robotic-assisted radical prostatectomy costs were $1111 higher than open approaches and $784 higher than laparoscopic approaches (P < .007).\(^16\)

RALP oncological outcomes appear to be at least equivalent to open approaches, with better perioperative outcomes compared with laparoscopic and open approaches. However, RALP is more costly than both, and comparisons of long-term oncologic and functional outcomes are sparse.
Partial Nephrectomy

Laparoscopic partial nephrectomy for renal masses is technically challenging due to the need for tumor excision and renal reconstruction under time constraints to reduce warm ischemia time (WIT). WIT has been associated with short- and long-term renal functional decline and serves as a proxy for surgeon proficiency in renal mass excision and renal reconstruction.17,18 The first robotic partial nephrectomy case series was described in 2004.19 Contemporary studies are limited to series ranging from 8 to 129 subjects, and were recently reviewed by Cha et al.20 Mean tumor size ranged from 1.8 to 3.0 cm. Mean operative times ranged from 82.7 to 265 minutes, EBL from 92 to 263 mL, and LOS from 1.5 to 4.8 days. Complications ranged from 0% to 20%, similar to conventional laparoscopy.21 Transfusions occurred in 3% to 10%, and were comparable with the 5.8% laparoscopic and 3.4% open likelihood for transfusions.22 WIT ranged from 17.8 to 33 minutes, comparable to a review of laparoscopic partial nephrectomy studies demonstrating WIT ranging from 27 to 35 minutes.23 In addition, positive margins ranged from 1.2% to 5.7%, comparable to laparoscopic and open approaches at 2.9% and 1.3%, respectively. Urine leaks occurred in 2% to 12.5% of subjects.

The largest retrospective comparative study compared 129 robotic and 118 laparoscopic partial nephrectomies, and demonstrated similar complications and postoperative renal function, but shorter WIT (19.7 vs 28.4 minutes; \( P < .001 \)), lower EBL (155 vs 196 mL; \( P = .003 \)), and shorter LOS (2.4 vs 2.7 days; \( P < .001 \)) in favor of robotics.21 This contrasts with earlier comparisons of robotic versus laparoscopic partial nephrectomy that did not demonstrate differences in EBL, operative time, or WIT.24-30 A recent retrospective series found that robotic and laparoscopic approaches have similar perioperative outcomes in the setting of moderate to high complexity tumors; however, robotic versus laparoscopic partial nephrectomy had fewer open conversions (1% vs 11.5%, \( P < .001 \)).31 A study of the Nationwide Inpatient Sample found that on a population-based level, robotic partial nephrectomy resulted in fewer complications and shorter LOS than both laparoscopic and open approaches (2.8 vs 3.6 vs 4.5 days, respectively; \( P < .001 \)).16 In addition, contrary to single-center studies, the median costs between surgical approaches were not significantly different.

Robotic partial nephrectomy is safe and cost-effective compared with open and laparoscopic approaches, and appears to provide clinical benefits over conventional laparoscopy, particularly for complex tumors.

Radical Cystectomy

Radical cystectomy is the gold-standard therapy for muscle-invasive bladder cancer, and the first robotic-assisted radical cystectomy (RARC) was reported in 2003. Orvieto et al recently reviewed perioperative outcomes of 24 studies of 350 RARC, including comparisons with laparoscopic radical cystectomy.32 Mean robotic operative times ranged from 140 to 410 minutes, EBL from 166 to 615 mL, transfusions from 5% to 43%, mean LOS from 5 to 11.6 days, with pelvic lymph node dissection yields ranging from 13 to 23. These outcomes were all comparable to open radical cystectomy series. Moreover, open conversions only accounted for 0% to 3%. Although promising, the studies were conducted by high-volume open and robotic surgeons, and these results may not be generalizable given that operative time, EBL, and lymph node yields of RARC are associated with prior RALP experience.33

In a prospective comparative study of 20 laparoscopic versus 12 RARC procedures, RARC operative times were similar to laparoscopic approach, whereas EBL was lower (212 vs 653 mL; \( P < .001 \)) and there were fewer transfusions (42.8% vs 70%; \( P < .0011 \)) with robotic assistance.34 Moreover, robotic assistance versus laparoscopy was associated with fewer intraoperative (7% vs 15%) and postoperative (21% vs 55%) complications; however, statistical analyses were not reported. A comparative study of 24 open versus 13 early experience RARC procedures found lower EBL (1250 vs 500 mL; \( P = .0002 \)), shorter LOS (10 vs 8 days; \( P = .044 \)), and longer operative times for RARC (395 vs 697 minutes; \( P = .0002 \)) with similar complication rates.35 However, there was no adjustment for selection bias, and patients selected for RARC were healthier with lower-stage cancers. To date, the largest series comparing 104 open versus 83 RARC (with no differences in comorbidities or pathologic features) demonstrated fewer 30-day complications with robotic assistance (59% vs 41%; \( P = .04 \)) as well as fewer major complications (30% vs 10%; \( P = .007 \)).36 The only randomized study, which compared 20 versus 21 open versus RARC procedures, demonstrated lower mean EBL (575 vs 258 mL; \( P < .0001 \)), lower analgesic requirements (147.4 vs 89.0 mg; \( P = .0044 \)), and earlier return to bowel function (4.3 vs 3.2 days; \( P = .0008 \)) in favor of robotic assistance.37 In addition, lymph node yields were comparable. A population-based study adjusted with propensity score methods demonstrated that robotic versus open radical cystectomy was associated with fewer complications, including deaths, and less need for parenteral nutrition (all \( P < .025 \)).38 However, LOS was similar, and RARC was $3797 more costly (\( P = .023 \)).

Disparate follow-up times obfuscate direct comparison of open versus RARC oncologic outcomes. Chade et al found that recurrence-free survival at 5 and 10 years following open radical cystectomy ranged from 62% to 68% and 50% to 60%, respectively, with overall 5- and 10-year survival ranging from 59% to 66% and 37% to 43%, respectively. By comparison, most robotic series report 1 to 2 years of follow-up, with disease-free and overall survival ranging from 86% to 91% and 90% to 96%, respectively.39
Owing to the higher incidence of bladder cancer among males, more than 75% of all RARC are performed in men.\textsuperscript{38,40} Neurovascular bundle preservation for erectile function is commonly performed, but no published functional outcomes are available. RARC in females is associated with higher EBL and operative times due to vaginal dissection. Irrespective of sex, open versus intracorporeal urinary diversion is more commonly performed, with ileal conduit diversion predominating over neobladders and catheterizable urinary stomas.\textsuperscript{32}

RARC compares favorably with open and laparoscopic approaches in terms of perioperative outcomes, with good short-term cancer control, albeit at higher costs.

**Hysterectomy and Trachelectomy**

Food and Drug Administration approval for robotic-assisted radical hysterectomy for endometrial and cervical cancers was conferred in 2005, and additional applications include pelvic lymphadenectomy and trachelectomy. Yim et al reviewed robotic-assisted gynecologic oncologic surgeries, which were predominantly composed of case series.\textsuperscript{41} For radical hysterectomy and lymphadenectomy, mean operative times ranged from 144 to 434 minutes, EBL from 50 to 355 mL, with 0% to 3% of endometrial cases requiring transfusions, and lymph node yields of 10.2 to 33.8. Open conversions were reported in 1% to 12% of cases.

Reza et al performed a meta-analysis\textsuperscript{42} of retrospective comparative studies for hysterectomy for endometrial cancer and found that robotic assistance offered shorter LOS (–2.68 days, 95% CI = –3.53, –1.84), lower risk of complications (odds ratio [OR] = 0.22, 95% CI = 0.13, 0.39) compared to open but similar to conventional laparoscopy, lower EBL versus open (–152.14 mL, 95% CI = –184.24, –120.04) and laparoscopic (–75.96 mL, 95% CI = –142.39, –9.53), with less need for transfusions than open (OR = 0.25, 95% CI = 0.07, 0.81) and laparoscopic (OR = 0.24, 95% CI = 0.09, 0.64) approaches. Robotics also had higher lymph node yields than open (+5.91; 95% CI = 0.13, 11.68). However, although robotic assistance operative times were similar to those of laparoscopy, they were longer than open surgeries (89.25 minutes, 95% CI = 51.59, 126.81). Robotic assistance was associated with lower odds of open conversion compared to laparoscopy (OR = 0.43, 95% CI = 0.21, 0.85). Moreover, robotic versus laparoscopic operative times have been shown to be shorter for obese women (189 vs 215 min, P = .004).\textsuperscript{43}

More recently, Wright et al retrospectively compared perioperative morbidity and complications in 2464 women that underwent either laparoscopic (n = 1027) or robotic (n = 1437) hysterectomy for endometrial cancer.\textsuperscript{44} After adjusting for patient, surgeon, and hospital characteristics, they found similar intraoperative, surgical, and medical complications, and hospitalizations exceeding 2 days. In addition, although the likelihood of overall complications were similar, laparoscopic versus robotic hysterectomy was associated with a greater likelihood for reoperations (0.8% vs 0.2%, respectively; P = .04). However, as pointed out in the accompanying editorial by Sukumar et al, this is relatively early in the adoption of robotic-assisted hysterectomy, and comparative effectiveness studies are needed with greater dissemination of robotic technique and overcoming individual surgeon learning curves.\textsuperscript{39}

Reza et al also evaluated hysterectomy for cervical cancer, with similar findings of shorter LOS with robotic versus open approaches (–2.05 days, 95% CI = –2.80, –1.29) and lower EBL (–337.17 mL, 95% CI = –459.44, –208.91) and transfusions (OR = 0.18, 95% CI = 0.07, 0.44). However, there were no differences in operative times, lymph node yields, positive margins, or complications compared with open approaches. With the exception of lower EBL with robotics (–63.52 mL, 95% CI = –100.49, –26.54), there were no differences in other outcomes compared with laparoscopy. Short-term robotic versus open progression-free and overall survival data were comparable at 3 years of follow-up.\textsuperscript{46}

Yim et al also identified 6 case reports/series of robotic-assisted radical trachelectomy for fertility preservation with pelvic lymphadenectomy for cervical cancer, totaling 17 subjects. Mean EBL ranged from 23 to 200 mL, operative times from 172 to 340 minutes, and lymph node yields of 20 to 43.\textsuperscript{41} Uterine artery preservation was performed in 8 cases. However, oncological and obstetrical results are currently unavailable.

Comparative cost studies demonstrate almost 2-fold higher costs for robotic-assisted versus laparoscopic techniques (€4067 vs €2151; P < .05) after controlling for age, body mass index, and uterine weight.\textsuperscript{47} Even after adjusting for variables such as surgeon experience and hospital characteristics, Wright et al found robotic hysterectomy to be $1291 more costly than laparoscopic approaches (95% CI = $985, $1597).\textsuperscript{44} However, after calculating for societal/productivity losses, robotic approaches demonstrate cost savings over open approaches, with mean costs of $8212 versus $12,943 (P = .0001), respectively.\textsuperscript{48}

Robotic hysterectomy offers intra- and perioperative advantages over open surgery, and for endometrial cancer appears to offer benefits over laparoscopy. Additional studies are needed for robotic-assisted trachelectomy for cervical cancer.

**Oropharyngeal Surgery**

Surgery of the oral cavity, oropharynx, hypopharynx, or larynx for malignancies all require magnified visualization and fine dissection. Conventional open approaches risk
poor cosmesis and dysfunctional speech and swallowing. Endoscopic laser surgery improves speed of recovery and cosmesis; however, visualization and instrument maneuverability are limited.\textsuperscript{49}

We identified 5 single-center prospective transoral robotic surgery (TORS) trials ranging from 18 to 54 subjects.\textsuperscript{50-54} Operative times ranged from 71 to 103 minutes, EBL from 12 to 189 mL, and hospital LOS from 1.5 to 3.8 days. There was only 1 study that reported conversions,\textsuperscript{53} which occurred in 11% due to technical reasons and 5.6% due to tumor infiltration. Complication rates were 0% to 31%, most of which were minor, which compares favorably to a large multicenter open series that demonstrated severe complications in up to 23% of patients ($P < .001$).\textsuperscript{55} There was variability in tumor characteristics between studies; however, the likelihood of positive margins ranged from 0% to 7.4%. Disease-free survival, with follow-up of 5.1 to 12.3 months, ranged from 90.3% to 100%. A total of 83.3% to 100% of subjects were without gastrostomies, which is comparable to transoral laser\textsuperscript{56} (91% at 24 months follow-up) and open series (47% for transhyoid and 45% for mandibulotomy at 5 years).\textsuperscript{57} One study evaluated speech and found that all approaches resulted in “normal speech” with mean follow-up of 12.3 months.\textsuperscript{52}

Although TORS is in its infancy compared to other robotic-assisted surgeries, it is technically feasible and provides reasonable outcomes compared with open and endoscopic approaches.

**Thyroidectomy**

The endoscopic approach to thyroidectomy has been challenging given the fine visualization and movements required for this delicate surgery. The robotic platform facilitates fine movements and has the potential for improved cosmesis compared with an open approach, thus leading to increased uptake of transaxillary gasless thyroidectomy. Korean centers have been at the forefront of adopting and refining this technique and have the largest reports of robotic thyroidectomy experience.

There were 2 comparative studies of robotic versus open thyroidectomy, 1 retrospective\textsuperscript{58} and 1 prospective nonrandomized,\textsuperscript{59} and 2 retrospective comparisons of robotic versus endoscopic approach.\textsuperscript{60,61} Several of the groups pooled their data to report the largest experience of 2014 robotic cases of total and subtotal thyroidectomy with modified radical neck or central compartment node dissections.\textsuperscript{62} Mean robotic operative times ranged from 110 to 168 minutes, compared with 87 to 134 minutes for open cases. Higher operative times were reported from the center that was early in its experience with robotic technology. Endoscopic, nonrobotic operative times were 126 to 142 minutes. Among all studies, there were no mortalities and there was only 1 open conversion due to bleeding. EBL was minimal and LOS was similar in the comparative studies, although hospitalization was 6.1 days from the early robotic experience group and shorter in the others (2.5-3.4 days). One study found significantly lower pain and analgesic use at 1 and 3 postoperative weeks ($P = .01$ and $P = .002$), and demonstrated better cosmesis ($P < .0001$) with robotic assistance versus open thyroidectomy.\textsuperscript{59} Robotic lymph node dissection yield was similar to that of open thyroidectomy\textsuperscript{57}; however, it exceeded that of endoscopy in 2 comparative studies from the same group (4.3 vs 3.6 nodes, $P < .001$, and 4.5 vs 2.4 nodes; $P = .004$).\textsuperscript{60,61} Moreover, there were no reported cancer recurrences. One comparative study noted a robotic learning curve of 35 to 40 cases, versus the endoscopic curve of 55 to 60 cases.\textsuperscript{61}

The robotic approach is feasible and less technically challenging than thyroid endoscopy. In addition to conferring better short-term postoperative outcomes than open thyroidectomy, it may offer comparable outcomes to endoscopy, and provides higher lymph node yields.

**Adrenalectomy**

Although the first robotic adrenalectomy was reported in 2001,\textsuperscript{64} it is currently recommended that adrenal cortical carcinoma be resected via an open en-bloc resection.\textsuperscript{65} However, minimally invasive approaches are routinely used for resection of benign and isolated metastatic lesions, and are considered safe for resection of pheochromocytomas with or without cortical sparing. There are no prospective comparisons of robotics to pure laparoscopy. The largest studies include 2 retrospective\textsuperscript{66,67} and 2 prospective\textsuperscript{68,69} single-center series, and 2 single-center retrospective comparative studies\textsuperscript{69,70} with 40 to 100 subjects. Robotic operative times ranged from 99 to 160 minutes, complications from 2% to 13% (with 2.4% mortality in 1 study\textsuperscript{66}), conversion to open or laparoscopy from 0% to 10%, and LOS from 1.1 to 6.4 days.

Brunaud et al\textsuperscript{70} compared 50 robotic to 59 laparoscopic adrenalectomies and found robotic cases had lower EBL (49 vs 79 mL; $P < .001$), which is consistent with other robotic series reporting EBL < 50 mL.\textsuperscript{66,67,71} Robotic cases were also associated with longer operative times (104 vs 87 minutes, $P = .003$). However, comparable operative times were noted among surgeons with experiences beyond 20 cases. In addition, operative times shortened by 1 to 2 minutes with 10 additional cases up to 100 cases, and also shortened with greater assistant training level ($P = .01$) and smaller tumor size ($P = .005$).\textsuperscript{68} Conversions, morbidity, and LOS were similar to laparoscopy. Cost modeling found robotics to be 2.3 times more expensive than laparoscopy ($€4155$ vs $€1799$).
Although there are smaller published robotic series concerned with the posterior retroperitoneal approach, most large studies focused on anterior or lateral transperitoneal approaches, with the exception of the series by Karabulut et al, in which 32 transperitoneal and 18 retroperitoneal laparoscopic and robotic approaches were compared. In addition, they evaluated steps of the operation, including docking, dissection, and hemostasis times. No variation in operative times was observed between anatomic and surgical approaches, despite an association between the robotic approach and larger tumor size (4.7 vs 3.8 cm; \( P = .05 \)). Docking times decreased by 50% during the second year of robotic implementation, as assistant surgeons gained greater experience. The likelihood of robotic open conversion was similar to laparoscopy (2% vs 4%), and when excluding conversions, robotics versus laparoscopy was associated with shorter LOS (1.1 vs 1.5 days; \( P = .006 \)).

Robotic adrenalectomy is safe and yields clinical outcomes similar to laparoscopy. Greater operative experience facilitates shorter operative times. However, the potential benefit of shorter hospitalizations for robotics has not been consistently demonstrated, and its benefit in the setting of higher costs requires further investigation.

Colorectal Surgery

Laparoscopic total mesorectal resection for cancer is feasible in the hands of high-volume surgeons. However, this approach is technically challenging due to pelvic anatomy and widespread use of neoadjuvant chemoradiation, which increases the degree of difficulty. A recent meta-analysis compared 344 robotic versus 510 laparoscopic rectal cancer resections across 8 studies.\(^7^2\) There were no differences in operative time, EBL, LOS, or time to regular diet; however, the robotic versus laparoscopic conversion rate to open surgery was significantly lower (2% vs 7%, \( P = .0007 \)). Complications were similar for robotic versus laparoscopic approaches (19.7% vs 18.8%), with similar anastomotic leak occurrences in 6.4% versus 6.8%, respectively. Likelihood of robotic versus laparoscopic mortality (0.7% vs 0.4%), wound infection (2.6% vs 3.6%), and ileus (4.9% vs 2.5%) were also similar. Positive circumferential margins were similar and found in 2.9% of robotic and 3% of laparoscopic cases, and distal resection margin lengths and lymph node yields were similar as well. In addition, there was selection bias for the robotic approach for lower-lying lesions, which are more technically challenging, and thus, robotic results may be more favorable, given the lack of adjusted outcomes.

Another systematic review totaling 434 robotic resections pooled robotic–only and comparative studies,\(^7^3\) overlapping somewhat with the aforementioned study. Robotic operative times ranged from 190 to 347 minutes and were generally longer than laparoscopy. Robotic EBL ranged from 50 to 283 mL and LOS ranged from 5 to 11.9 days, similar to laparoscopy. The frequency of robotic-assisted complications was 31.3%, with 8.3% experiencing anastomotic leaks.

In addition, a 2012 systematic review of robotic colorectal surgery synthesized results from case series of 440 low anterior and 149 intersphincteric and abdominoperineal resections.\(^7^4\) This review combined data for intersphincteric and abdominoperineal approaches, and revealed that operative times (263.3 [180-450] vs 199.6 [180-270] minutes), and LOS (9.2 vs 5.7 days) were higher among intersphincteric and abdominoperineal than low anterior resections, although no statistical analyses were reported. The same applied for postoperative complications (61.5% vs 8.9%). Of the 14 articles concerned with intersphincteric and abdominoperineal approaches, just 1 reported a combined anastomotic leak rate of 40.9%. Anastomotic failure occurred in 3.8% of low anterior rectal resections. There were no conversions among intersphincteric/abdominoperineal approaches and only 0.4% of low anterior resections converted to open, lower than the 12% to 20% laparoscopic-to-open conversion rate reported from high-volume centers. Mean lymph node yield for intersphincteric/abdominoperineal robotic cases was 14.3 (10.3-20.6), which was comparable to laparoscopy and greater than the 11-node threshold established by the College of American Pathologists.\(^7^5\) No differences in overall survival were observed, with 100% and 97% survival at 10\(^7^6\) and 17.4\(^7^7\) months, respectively.

Antoniou et al\(^7^4\) also systemically reviewed 210 right and 178 left colon and sigmoid resections. Operative times ranged from 167 to 185 minutes and EBL 24.5 to 100.6 mL. LOS was 5.2 to 5.9 days and complications occurred in 13.5% to 18.1%. Conversions occurred in 2% of right colon and 8% of left/sigmoid colon resections, which is comparable to laparoscopic conversion rates (14%-41%).\(^7^8\)\(^7^9\)

Robotic approaches to colorectal resection are feasible, confer acceptable short-term oncologic outcomes, and have fewer conversions than laparoscopy. However, robotic assistance has not been shown to confer improved LOS or complication rates. In addition, there is an absence of sexual or urinary function outcomes. Moreover, robotic rectal surgery is more costly compared to laparoscopic and open approaches ($14,080 vs $9,120 and $8,386, respectively; \( P < .01 \)).\(^8^0\) Although our discussion is limited to meta-analyses and systematic reviews, there is an ongoing international multicenter prospective randomized controlled trial\(^8^1\) that will help determine whether the higher cost of robotics is offset by clinical benefit compared with laparoscopy.

Pancreatectomy

Due to high complexity and long learning curve, laparoscopic pancreatic resection has not gained widespread adoption. The robotic approach was first reported in 2003 by...
Giulianotti et al,66 and their series of 134 benign and malignant cases is the largest single-surgeon experience of robotic pancreatic surgeries. Mean operative time was 331 minutes (range, 75-660 minutes), transfusion rate was 7%, and LOS was 9.3 days (range, 3-85 days); comparable to open and laparoscopic experiences. The 10.4% conversion rate is similar to reported laparoscopic conversions of 13.8%,82 and was attributed to tumor characteristics precluding minimally invasive excision rather than technical factors. Complications occurred in 26% and mortality was 2.2%, comparing favorably with open pancreatic surgery outcomes of 40% and 5%, respectively.83,84 Of the 103 subjects who underwent pancreatotomy, 27% developed pancreatic fistulas, much higher than the 5% to 7.7% from open series.83,85 However, only one required reoperation, whereas laparoscopic series have reported reoperations in 7% to 30%.83 Positive margins occurred in 4.9% and increased to 21% with larger tumor sizes. Mean lymph node yield was 18 (range, 5-45), which is comparable to large open series.84

The second largest series reported 30 pancreatic resections from 5 high-volume pancreatic surgeons at a single institution, with median operative time of 512 minutes (range, 327-848 minutes) and LOS of 9 days (range, 4-87 days). Median EBL was 320 mL (range, 50-1000 mL), which is less than half that of open series. Perioperative mortality was 3.3% and complications occurred in 50%, with 27% classified as Clavien III/IV (which require procedural intervention), and are comparable to open series. Moreover, 27% developed pancreatic fistulas, similar to the previous study.86

The robotic approach facilitates the minimally invasive approach for these complex surgeries. However, similar to open surgery, robotic pancreatic reconstruction is fraught with a relatively high likelihood of complications. Moreover, these reports from highly experienced pancreatic surgeons have yet to demonstrate significant clinical benefit.

**Hepatectomy**

The anatomic location, size, and vascularity of the liver contribute to the technically challenging nature of minimally invasive hepatic resection. Only single-center robotic series comprise the current literature, and the largest included 70 resections by a single surgeon, of which 60% were for malignancy and 48.5% had previous abdominal surgery.87 Major resections involving 3 or more segments were performed in 38.5%. Median operative times for major and minor resections were 313 minutes (range, 220-480 minutes) and 198 minutes (range, 90-459 minutes), respectively, and were comparable to published laparoscopic series.88,89 Median EBL for major versus minor resections were 300 mL (range, 100-2000 mL) versus 150 mL (range, 20-1800 mL), respectively, with 21.4% transfusions. Moreover, 5.7% of major resections required conversion to open surgery versus no conversions for minor resections, consistent with the 5% to 15% range of open conversion from laparoscopic series.88-91 There were no mortalities and overall complications were 21% (11.4% were major), which is comparable to existing laparoscopic and open series. Median LOS was 7 days (range, 2-26 days). All surgical margins were negative with median margins of 18 mm (1-70 mm), which are greater than large open and laparoscopic series (5.2-15.3 mm).80,92 The authors note that no conclusions can be drawn regarding learning curves given that the robotic series were performed over a 7-year period, with approximately only 10 cases per year.

A study with 13 robotic cases demonstrated comparable robotic versus open operative time (338 [150-720] vs 205 [65-340] minutes), EBL (280 vs 470 mL, none requiring transfusion) without open conversions, LOS (6.7 vs 9.6 days),83 and a 7.8% vs 12.5% complication rate. Moreover, compared with previous open cases, the robotic approach was $12,046 more costly, although statistical analyses were not reported.93

Robotic hepatectomy appears to be safe when performed by experienced surgeons and offers similar results compared with laparoscopic and open approaches; however, series are small and not generalizable.

**Pulmonary Lobectomy**

Video-assisted thoracoscopic surgery (VATS) for the resection of lung malignancies has been associated with shorter LOS, less pain, and improved delivery and tolerance to adjuvant chemotherapy in comparison with open lobectomy.94-97 Despite these advantages, VATS is used in less than 20% of lobectomies, possibly due to limitations of visualization and maneuverability of the approach. Robotics improves maneuverability; however, the mediastinal view is still limited, and robotic instruments are targeted toward fine dissection, limiting its ability to manipulate lung tissue.

The 2 largest case series of robotic-assisted lobectomies include 1 single-center experience of 100 subjects98 and another comprising 325 subjects from 3 centers.99 Operative times were 216 and 206 minutes, which shortened significantly after the first 20 and 50 cases, respectively. EBL was not reported. Open conversions were required in 1% and 5%, and LOS was 4 and 5 days, respectively. Overall, complications occurred in 21% and 25.2%, with 3.7% representing major complications. Death occurred in 3% and 0.3%, all attributable to postoperative medical causes. In the single-center series, the disease-free survival at a median follow-up of 32 months was 92%, and in the multicenter series, the overall 5-year survival was 80%. However, the retrospective and noncomparative nature of these studies precluded adjustment for potential patient and tumor selection biases. Conversions, operative times, LOS, complications, mortality, and oncologic outcomes were consistent with previous reports of VATS outcomes.94,95,100
The robotic approach confers advantages over open surgery similar to VATS and is safe with outcomes comparable to VATS. However, existing data do not demonstrate superiority over VATS, and comparative effectiveness studies are needed to explore short-term outcomes such as pain and respiratory function and to assess cost differences.

Esophagectomy

Minimally invasive esophagectomy is technically challenging but has been associated with lower EBL and shorter intensive care unit and hospital stays relative to open approaches. Robotic experiences are limited to small single-center series ranging from 4 to 25 cases, which were systematically reviewed by Clark et al. There was great variability in surgical approaches, including robotic transthoracic and/or transhiatal approaches with or without thoracotomy, laparoscopy, or laparotomy, with variations in positioning including supine, lateral, and prone. Median operative times ranged from 173 to 666 minutes and open conversions occurred in 7%. EBL ranged from 0 to 400 mL and mean LOS was 15 days (mean range, 10-22 days). Reporting of complications varied, with major complications occurring in 29% to 32%, with 18% (range, 14%-33%) anastomotic leaks and 2.4% 30-day mortality. Lymph node yields ranged from 12 to 38, and disease recurrence was 14%. No positive surgical margins were reported, and lymph node yields ranged from 13 to 43. Two series reported disease-specific survival, and there were no recurrences at mean follow-up ranging from 9.7 to 12.2 months. However, patient selection may play a role, because more than 95% of subjects had stage I and II disease. One nonrandomized comparative study demonstrated 2-fold lower EBL (P = .0312) and 1.6-day shorter LOS compared with open approaches, and 1.4-day shorter LOS compared with laparoscopy (P < .001). However, mean LOS was similar to open approaches for both total (11 [8-30] vs 12 [8-34] days) and subtotal gastrectomy (9 [8-12] vs 9 [7-22] days) in another study. In addition, robotic assistance was associated with longer operative times than laparoscopy for subtotal gastrectomy (230 vs 134.1 minutes; P < .001).

Similarly to robotic esophagectomy, reported gastric resection outcomes vary widely but appear to have shorter LOS and comparable short-term oncologic outcomes compared with open and laparoscopic approaches. However, robotic operative times are significantly longer.

Conclusion

There is little comparative evidence from randomized controlled trials, and any outcomes from such study designs are affected by variation in surgeon training and experience, which is difficult to assess and adjust for statistically. Consequently, the influence of intrasurgeon technical heterogeneity may outweigh differences in surgical approach. However, population-based, observational studies demonstrate fewer complications for robotic-assisted procedures such as radical prostatectomy and radical cystectomy, in which there are more than 5 years of adoption and dissemination.

Macroscopically, the challenge for the financially strapped US health care system is to limit potentially misleading marketing claims by providers who have invested millions of dollars to acquire and maintain robotic systems. In contrast, in more-regulated international 1-payer healthcare systems where the cost of the robotic instruments are passed directly to the patient, there has been limited adoption. For instance, the Canadian health care system has more limited numbers of robotic systems relative to the US health care system, allowing a limited number of surgeons to quickly develop expertise, creating centers of excellence, and sparing, to a greater degree, the compromise in patient outcomes that is inevitable during surgeon learning curves for novel procedures.

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