**Mini-invasive Surgery**

Mini-Review

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# Robot-assisted *vs.* laparoscopic rectal cancer resection: a narrative review of oncological outcomes, functional results, and future perspectives

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**How to cite this article:** Ueda K, Iwamoto M, Yane Y, Makutani Y, Yoshioka Y, Daito K, Haeno M, Umeda I, Tokoro T, Gagner M, Kawamura J. Robot-assisted *vs.* laparoscopic rectal cancer resection: a narrative review of oncological outcomes, functional results, and future perspectives. *Mini-invasive Surg.* 2025;9:21. https://dx.doi.org/10.20517/2574-1225.2025.38

**Received:** 28 Mar 2025 **First Decision:** 9 Jun 2025 **Revised:** 23 Jun 2025 **Accepted:** 4 Jul 2025 **Published:** 10 Jul 2025

**Academic Editor:** Giulio Belli **Copy Editor:** Pei-Yun Wang **Production Editor:** Pei-Yun Wang

## Abstract

Robot-assisted rectal resection has increasingly gained acceptance as a minimally invasive surgical approach for rectal cancer, primarily due to its enhanced precision, dexterity, and superior visualization compared to traditional laparoscopic surgery. Accumulating evidence from randomized controlled trials, systematic reviews, and large-scale national registry analyses underscores its feasibility and safety, particularly in technically demanding scenarios such as male patients, obese individuals, and those with low rectal tumors. Robotic surgery demonstrates favorable short-term outcomes, including significantly lower conversion rates, reduced intraoperative blood loss, and accelerated postoperative recovery. Nonetheless, results regarding operative duration, postoperative complications, and cost-effectiveness remain heterogeneous. Additionally, robotic techniques may facilitate improved functional preservation, especially concerning urinary and sexual functions, attributed to superior visualization and precise nerve-sparing capabilities; however, these benefits require further rigorous validation. Continued advancements in robotic technology and growing surgical proficiency necessitate future large-scale, multicenter trials to definitively establish the long-term oncological and functional advantages. Emerging robotic platforms and technological innovations hold promise for reducing costs and enhancing accessibility. This narrative review critically examines current evidence, outlining the clinical benefits, inherent limitations, and prospective advancements in robotic-assisted surgery for rectal cancer.

**Keywords:** Rectal cancer, robot-assisted surgery, cost-effectiveness, functional outcomes, technological advancements

## INTRODUCTION

Minimally invasive surgery has become the standard of care for colorectal malignancies due to improved short- and long-term outcomes compared to open techniques. Several randomized controlled trials (RCTs) have compared laparoscopic surgery (LS) and open surgery (OS) for colorectal cancer, evaluating their safety, efficacy, and oncological outcomes[1-5].

On the other hand, the rectum is located deep within the pelvis and is surrounded by autonomic nerves responsible for urinary and sexual functions, which makes surgical procedures particularly challenging. Compared to OS, LS offers advantages such as reduced blood loss and faster postoperative recovery. However, due to anatomical constraints, laparoscopic rectal surgery remains technically demanding.

From an oncological perspective, total mesorectal excision (TME) was introduced by Heald *et al.* as a surgical technique designed to enhance oncological outcomes in the treatment of rectal cancer. TME is based on the principle of en bloc resection of the entire mesorectum, which contains lymphatic drainage, blood vessels, and connective tissue surrounding the rectum. The key oncological rationale behind TME is that rectal cancer spreads within the mesorectal envelope, making precise dissection along embryological planes critical for achieving complete tumor resection and reducing local recurrence[6,7].

Robot-assisted surgery (RAS) was developed to enhance precision and minimize invasiveness in surgical procedures. The utility of RAS is well-documented, offering significant advantages over conventional OS and LS, including improved dexterity, greater precision, three-dimensional (3D) high-definition (HD) visualization, and enhanced surgeon ergonomics[8-10]. The unique capabilities of RAS make it an ideal approach for rectal cancer. These advantages contribute to improved oncological outcomes, better preservation of autonomic nerves, and higher rates of sphincter preservation compared to conventional techniques.

In this review, we summarize the latest evidence supporting the use of RAS in rectal cancer treatment, highlighting its impact on oncologic radicality, functional preservation, and patient outcomes. Furthermore, we discuss the future perspectives of robotic technology in rectal cancer surgery, including its potential to enhance minimally invasive techniques and patient-centered care further.

## METHODS

### Literature search strategy and study selection

To explore the comparative outcomes of RAS and LS for rectal cancer, we utilized the AI-based scientific search engine Consensus to conduct an initial literature search. The following keywords were entered: “robot-assisted surgery”, “laparoscopic surgery”, and “rectal cancer”. The search was limited to studies published between January 2015 and June 2025.

The Elicit and Consensus platform was used to identify relevant literature, with a particular focus on three types of high-level evidence: RCTs, meta-analyses, and nationwide registry studies. For each potentially eligible study, the sources were subsequently retrieved and verified through PubMed or the respective journal websites to ensure accuracy, assess methodological quality, and obtain full-text access for in-depth review.

All included studies were then carefully reviewed and synthesized to evaluate both short- and long-term clinical outcomes associated with RAS *vs.* LS for rectal cancer. This approach enabled a structured and evidence-based comparison grounded in up-to-date and peer-reviewed literature. In addition to database verification, methodological quality of included studies was assessed using the Cochrane Risk of Bias (ROB) tool for RCTs and the AMSTAR 2 tool for meta-analyses[11,12]. The PRISMA 2020 guideline was followed for literature selection and data synthesis, although no flow diagram is included due to the narrative nature of this review[13].

## THE TECHNOLOGY OF RAS

RAS has emerged as a transformative advancement in minimally invasive surgery, particularly in the management of rectal cancer. The integration of robotic platforms, such as the Da Vinci® Surgical System (Intuitive Surgical, Sunnyvale, CA, USA), offers enhanced precision, improved dexterity, and superior visualization, effectively addressing the limitations of conventional LS. This section outlines the technological foundations of RAS in rectal cancer treatment, highlighting its principal advantages and ongoing innovations.

### 3D HD vision

RAS offers a 3D, HD, and magnified view (up to 10-fold) of the surgical field, providing improved depth perception compared to the two-dimensional imaging of conventional laparoscopy. This enhanced visualization is especially advantageous in the confined pelvic space, where precise dissection around the mesorectum and pelvic autonomic nerves is essential to achieving optimal oncologic and functional outcomes[14].

### Wristed instrumentation and tremor filtration

The robotic platform employs wristed instruments (EndoWrist™) that provide seven degrees of freedom, closely mimicking the flexibility of the human wrist while enhancing dexterity. This feature facilitates complex maneuvers, such as precise suturing and dissection within the narrow pelvic cavity. Furthermore, robotic systems effectively filter out physiological hand tremors, improving stability and accuracy during delicate procedures[15].

### Ergonomic surgeon console and remote operation

In contrast to conventional laparoscopy, where the surgeon operates while standing and directly manipulating instruments, RAS allows surgeons to operate from a console in an ergonomically optimized seated position, thereby reducing physical strain. This setup enhances operator comfort, reduces fatigue, and may improve performance, particularly during lengthy rectal cancer procedures[16].

## RECENT EVIDENCE OF RAS FOR RECTAL CANCER

In recent years, RAS has seen growing adoption in the treatment of colorectal cancer. Several RCTs comparing RAS and LS have been conducted, yielding mixed results. Table 1 summarizes recent RCTs evaluating RAS for rectal cancer (RARCS).

### The penetration and adoption trends of RARCS

Over the past decade, the global adoption of RARCS has increased significantly, driven by improved surgeon proficiency, technological advancements, and broader institutional investment in robotic

**Table 1. Summary of the RCTs and their reported outcomes**

| Authors [ref.] (Trial name) | Study focus | Sample size (*n*) | Key outcomes |
|---|---|---|---|
| Jayne *et al.*[14] (ROLARR Trial) | Conversion rates in rectal cancer | 471 | No significant difference in conversion rates (8.1% RAS *vs.* 12.2% LS, *P* = 0.16). No clear benefit in oncological outcomes |
| Corrigan *et al.*[17] (ROLARR Trial) | Impact of surgeon experience on outcomes | 471 | Adjusting for the learning curve, RAS had a lower conversion rate (OR = 0.40, *P* = 0.038), suggesting robotic advantages with experience |
| Kim *et al.*[18] | TME quality and functional outcomes | 163 | No difference in TME quality or morbidity<br>RAS had better sexual function at 12 months (*P* = 0.03) |
| Feng *et al.* and Xu *et al.*[19,20] (REAL Trial) | Short- and long-term oncologic outcomes in rectal cancer | 1,240 | RAS had lower CRM positivity (4.0% *vs.* 7.2%, *P* = 0.023) and lower complication rates (16.2% *vs.* 23.1%, *P* = 0.003)<br>RAS had significantly lower LRR (RAS: 1.5% *vs.* LS: 4.0%, *P* = 0.025, HR = 0.451, 95%CI: 0.221-0.921) and DFS (RAS: 87.3% *vs.* LS: 83.6%, *P* = 0.035) |
| Park *et al.*[21] (COLRAR Trial) | TME quality and short-term outcomes in rectal cancer | 295 | No significant difference in TME completeness (80.7% RAS *vs.* 77.1% LS). RAS had a lower positive CRM rate (0% *vs.* 6.1%, *P* = 0.031) and shorter opioid use |

RCTs: Randomized controlled trials; RAS: robot-assisted surgery; LS: laparoscopic surgery; OR: odds ratio; TME: total mesorectal excision; CRM: circumferential resection margin; LRR: local recurrence rate; HR: hazard ratio; DFS: disease-free survival.

platforms. According to national registry data, the utilization of RARCS has steadily risen. For example, a nationwide Dutch registry reported that the proportion of rectal cancer resections performed robotically rose from 15% in 2018 to 22% in 2020, with RAS preferentially employed for technically demanding cases, such as low rectal tumors and male patients with narrow pelvises[22]. Similarly, in South Korea, a tertiary center database revealed that over 54% of rectal cancer resections were performed robotically by 2018, reflecting rapid and widespread institutional adoption[23].

Germany shows a more gradual uptake: a multicenter analysis of colorectal cancer surgeries in 36 German hospitals from 2019 to 2023 found that 1,758 out of 2,525 minimally invasive cases (approximately 9.8%) utilized robotic systems; rectal cancer–specific data were not separately quantified, but the figure suggests that robotic rectal resections currently represent less than 10% of minimally invasive approaches in routine German practice[24].

Norway occupies an intermediate position, with national data from 2022 indicating that approximately 50% of rectal cancer surgeries were performed using robotic assistance[25]. These regional disparities likely result from differences in healthcare infrastructure, reimbursement policies, surgeon training programs, centralization of rectal cancer care, and cost–benefit assessments.

In addition to national registry data, recent multicenter European cohort data provide further insights into RARCS uptake. A large retrospective study involving expert centers in the United Kingdom, the Netherlands, and France reported that between 2014 and 2024, 1,749 patients underwent minimally invasive rectal cancer surgery, of whom 60.3% (1,054/1,749) underwent robot-assisted procedures. This figure reflects a substantial real-world adoption of RARCS in Western Europe, particularly in high-volume centers with surgeons beyond their learning curves[26].

### Technical feasibility

The technical feasibility of RARCS has been well established, with several studies reporting consistently low conversion rates and high rates of complete TME; for example, the VITRUVIANO trial reported a 0% conversion rate to OS and a 98.4% TME completeness rate, even in advanced-stage tumors operated by certified robotic surgeons[17,27].

### Operative time

Operative time is generally longer with RAS. A recent meta-analysis of 13 RCTs reported an average increase of 41.5 min (95%CI: 22.15-60.81, $P < 0.001$) compared to LS, particularly in rectal procedures requiring pelvic docking[28].

### Intraoperative blood loss

RAS is associated with reduced blood loss, as demonstrated by a meta-analysis of 56 studies involving over 25,000 patients, which reported a weighted mean difference of -24.56 mL (95%CI: -30.10 to -18.98, $P < 0.00001$) in favor of RAS over LS and OS[29].

### Conversion rate

Multiple RCTs and pooled analyses consistently report lower conversion rates with RAS. For instance, the REAL trial reported a conversion rate of 1.7% for RAS *vs.* 3.9% for LS ($P < 0.05$), and the meta-analysis by Thrikandiyur *et al.* showed a relative risk (RR) of 0.57 (95%CI: 0.37-0.85, $P = 0.007$) for conversion with RAS[19,28]. An analysis of the Japanese National Cancer Database (NCD) using propensity score matching (PSM) revealed a significantly lower conversion rate with RAS compared to LS (0.7% *vs.* 2.0%, $P \leq 0.001$)[30]. Similarly, the Dutch registry reported a statistically significant reduction in conversion rate in the RAS group compared to the LS group (4% *vs.* 7%, $P = 0.003$)[22].

### Sphincter preservation in RARCS

Several studies suggest that RAS may improve sphincter preservation rates in low rectal cancer. The REAL trial reported a higher rate of low anterior resection and fewer abdominoperineal resections in the RAS group, attributed to greater precision in deep pelvic dissection[19]. Similarly, the COLRAR trial and Park *et al.* demonstrated the feasibility of intersphincteric resection using RAS, even in male or obese patients with tumors ≤ 5 cm from the anal verge[21]. The VITRUVIANO trial reported a low APR rate (5.3%) in a high-volume robotic setting, emphasizing the importance of surgeon expertise in optimizing sphincter preservation outcomes[27].

Collectively, these studies suggest that robotic-assisted rectal surgery can enhance the rate of sphincter-preserving procedures, particularly for low-lying tumors, owing to its precise and stable dissection capabilities. However, further trials with sphincter preservation as a primary endpoint and standardized functional assessments are warranted.

### Postoperative complications

Short-term postoperative complications in RAS are generally comparable to, or slightly lower than, those observed with LS. In the REAL trial, the rate of Clavien–Dindo (CD) grade II or higher complications was significantly lower in the RAS group (16.2%) than in the LS group (23.1%, $P = 0.003$)[19]. However, other RCTs, such as ROLARR, found no significant difference (33.1% in RAS *vs.* 31.7% in LS)[14]. A Japanese NCD study also showed no significant difference in major postoperative complications (CD grade III or higher): 9.4% in RAS *vs.* 10.6% in LS, $P = 0.117$)[30]. Regarding anastomotic leakage, both the Dutch registry and the Japanese NCD study reported similar rates between RAS and LS (16% in both groups, and 7.8% in RAS *vs.* 8.8% in LS, $P = 0.172$)[22,30].

### Postoperative hospital stay

RAS is associated with shorter hospital stays in meta-analyses. For example, Zhang *et al.* reported a mean reduction of 1.93 days (95%CI: -2.52 to -1.35, $P < 0.00001$) compared to LS[29]. However, the Dutch audit report showed a slightly longer median hospital stay in the RAS group (6 *vs.* 5 days, $P < 0.001$)[22]. Meanwhile, the Japanese NCD study found a modest reduction in median hospital stay in the RAS group

(13 days) compared to the LS group (14 days)[30].

### Oncologic outcomes (pathological evaluation of circumferential resection margin)

Oncologic outcomes, including CRM positivity and long-term recurrence, are generally equivalent to or slightly improved with RAS. In the ROLARR trial, the circumferential resection margin (CRM) positivity rate was 6.3% for conventional LS and 5.1% for RAS, with no significant difference[14]. In contrast, the REAL trial demonstrated a significantly lower CRM positivity rate in the RAS group (4.0% *vs.* 7.2%, $P$ = 0.023), as well as a 3-year locoregional recurrence rate of 1.5% for RAS *vs.* 4.0% for LS ($P$ = 0.025)[19]. The VITRUVIANO trial reported a CRM positivity rate of 4.6% overall. Among patients with stage II or III disease, the rate remained low at 6.0%, outperforming historical Japanese data, such as the 8.6% reported in the PRODUCT trial[31].

In addition to individual RCTs, a comprehensive Bayesian network meta-analysis by de'Angelis *et al.* incorporating 27 RCTs ($n$ = 8,696) further supports the oncologic advantages of RAS over LS for rectal cancer[32]. The analysis demonstrated that RARCS was significantly associated with a lower risk of incomplete TME (OR: 0.68; 95%CI: 0.46-0.94; $P$ = 0.02) and retrieved a greater number of lymph nodes (mean difference: 1.24; 95%CI: 0.10-2.52; $P$ = 0.03) compared to LS. While the odds of positive CRM were not significantly different (OR: 0.63; 95%CI: 0.37-1.07; $P$ = 0.07), the surface under the cumulative ranking curve (SUCRA) indicated that RARCS ranked second only to transanal TME in terms of CRM clearance and completeness of excision. These findings reinforce the pathological advantages of RAS in achieving optimal oncologic quality.

### Urogenital and sexual function

RAS may confer benefits in postoperative functional recovery. In the RCT by Kim *et al.*, male patients in the RAS group demonstrated significantly better sexual function at 12 months ($P$ = 0.03), and other studies have reported trends toward improved urinary continence, potentially due to the robotic platform's enhanced nerve-sparing capabilities[18]. A meta-analysis by Fleming *et al.*, involving 1,286 patients, showed that RARCS resulted in significantly better male urinary and sexual function compared to laparoscopy, with lower International Prostate Symptom Scores (IPSS) at 6 and 12 months and improved changes in International Index of Erectile Function (ΔIIEF) scores. Evidence regarding functional benefits in female patients remains limited and inconsistent[33].

### Long-term outcomes

In terms of long-term survival, outcomes for RAS and LS appear to be largely comparable. The extended analysis of the ROLARR trial showed no significant difference in disease-free survival (DFS) (HR: 1.030, 95%CI: 0.713-1.489, $P$ = 0.874) or overall survival (OS) (HR: 0.945, 95%CI: 0.530-1.686, $P$ = 0.848)[14]. The extended analysis of the ROLARR trial showed no significant difference in DFS (HR: 1.030, 95%CI: 0.713-1.489, $P$ = 0.874) or OS (HR: 0.945, 95%CI: 0.530-1.686, $P$ = 0.848)[17]. Conversely, the REAL trial demonstrated a modest but statistically significant improvement in 3-year DFS favoring RAS (87.3% *vs.* 83.6%, $P$ = 0.035), although OS did not differ significantly[20].

Conversely, the REAL trial demonstrated a modest but statistically significant improvement in 3-year DFS favoring RAS (87.3% *vs.* 83.6%, $P$ = 0.035), although OS did not differ significantly. The discordance in survival outcomes across RCTs may be attributed to differences in surgeon experience, patient selection, and tumor location. For example, the ROLARR trial included a significant learning curve phase, which may have attenuated the benefits of RAS, whereas the REAL trial involved high-volume centers with experienced robotic surgeons[20].

More recently, a UK single-center PSM cohort study reported a significantly higher 5-year OS in the RAS group compared to the LS group (81.7% *vs.* 72.4%, $P = 0.029$), while 5-year DFS showed a non-significant trend favoring RAS (74.4% *vs.* 63.9%, $P = 0.086$). Local recurrence (4.7% *vs.* 5.2%, $P = 0.850$) and distant recurrence (13.5% *vs.* 16.9%, $P = 0.390$) were comparable between the groups[34]. These results suggest that while oncologic outcomes such as DFS and recurrence remain similar, RAS may be associated with improved long-term OS in selected cohorts. However, the underlying factors contributing to this OS benefit remain uncertain and warrant further investigation in prospective studies.

### Cost-effectiveness

RARCS remains significantly more expensive than LS. The ROLARR trial reported an additional cost of £980 (≈$1,132) per case for RAS, excluding capital and maintenance expenses, which added an additional $1,611 per procedure[14]. In the COLRAR trial, RAS was found to be 2.3 times more expensive than LS, with patients incurring $6,000-$8,000 in out-of-pocket expenses due to limited insurance reimbursement[21]. Although the REAL trial demonstrated clinical benefits of RAS, it also acknowledged its substantial economic burden[19,20].

The economic disadvantage of RAS is particularly pronounced in countries like Japan, where the procedure-based national insurance system provides the same reimbursement for robotic and laparoscopic procedures. However, it does not account for additional costs related to robotic instruments, maintenance, and depreciation of capital equipment, resulting in considerable financial pressure on hospitals[35].

In contrast, South Korea employs a mixed reimbursement model, where RARCS is not covered under the National Health Insurance but can be partially subsidized through private insurance or out-of-pocket payments. This structure enables selective institutional adoption of RAS in high-volume centers. Similarly, in the United States, private insurers may cover robotic procedures depending on the policy, and Medicare provides partial coverage. Notably, U.S. hospitals may offset the high upfront investment in robotic platforms through bundled payment programs and reduced postoperative complication rates, which translate into shorter lengths of stay and fewer readmissions.

From an economic modeling perspective, a recent prospective cost-utility analysis from Spain (ROBOCOSTES trial) provides valuable insight[36]. In this national study, RARCS was associated with higher direct costs - an incremental cost of €919.66 (≈$995) compared to LS - but also yielded better postoperative quality-adjusted life years (QALYs). QALYs at 30 and 90 days favored RAS (0.8914 *vs.* 0.8139 at 30 days; 0.9573 *vs.* 0.8740 at 90 days), and at a willingness-to-pay threshold of €20,000-30,000 (≈$21,600-$32,400), there was an 84%-89% probability that RAS was more cost-effective than LS.

These findings suggest that when short-term quality-of-life improvements and long-term institutional benefits are considered, RAS may offer value despite higher initial costs. However, it is important to note that such findings are derived from the Spanish healthcare system. In Asian countries like Japan or South Korea, where reimbursement structures differ significantly and robotic-specific expenses are not universally covered, the cost-effectiveness of RAS remains context-dependent. Future improvements in robotic platform affordability, procedural standardization, surgeon experience, and reductions in complication rates may progressively enhance the economic viability of RAS across diverse healthcare systems.

### Challenges of RARCS

Building upon the discussion of technological advancements and the future integration of AI and AR in rectal surgery, it is equally important to examine the clinical limitations and real-world applicability of RARCS.

Emerging evidence has identified specific patient subgroups that may derive greater benefit from RARCS compared to conventional LS. These include anatomically challenging cases such as male patients, individuals with obesity, those with a narrow pelvis, and patients with low-lying tumors - scenarios in which pelvic dissection is inherently more complex.

Kim *et al.* reported that RARCS significantly improved pelvic autonomic nerve preservation and postoperative functional outcomes in patients with low rectal cancer and narrow pelvic anatomy, thereby reducing the risk of urinary and sexual dysfunction[18]. Similarly, Matsuyama *et al.* demonstrated that in male and obese patients, RARCS was associated with lower conversion rates, reduced intraoperative blood loss, and shorter hospital stays compared to LS[37]. The REAL trial further reinforced the oncologic precision of RARCS, showing significantly lower rates of positive CRM and locoregional recurrence in patients with low rectal tumors[20].

In addition, robotic platforms have shown promise in technically demanding procedures such as lateral lymph node dissection (LLND), where deep pelvic anatomy and complex vascular structures increase operative difficulty. A multicenter study reported that robotic LLND was associated with shorter operative time, reduced blood loss, and fewer complications, without compromising oncologic outcomes[38]. Similarly, in patients who received neoadjuvant chemoradiotherapy (nCRT) - which induces pelvic fibrosis and distorts tissue planes - RARCS enabled greater sphincter preservation and maintained oncologic safety, even in those with low-lying or advanced tumors[39].

Together, these findings underscore the clinical and oncologic benefits of RARCS in managing anatomically and technically complex pelvic conditions. Clear identification of optimal patient subgroups not only enhances surgical outcomes but also supports more personalized, evidence-based application of robotic platforms in rectal cancer treatment.

## FUTURE PERSPECTIVES FOR RARCS

RAS is expected to become an increasingly central component in the minimally invasive treatment of rectal cancer, especially in anatomically challenging cases. The recent introduction of alternative robotic platforms - such as the Hugo™ RAS system (Medtronic, Dublin, Ireland), Versius® (CMR Surgical, Cambridge, UK), Senhance® (Asensus Surgical Inc., NC, USA), and Hinotori™ (Medicaroid Corp., Kobe, Japan) - is anticipated to enhance accessibility by offering more cost-effective and modular solutions compared to the da Vinci® system. These developments may contribute to the broader dissemination of robotic surgery across diverse healthcare settings.

Further advancements - including integration with artificial intelligence (AI), real-time navigation, and augmented reality - may enhance surgical precision, facilitate nerve preservation, and enable individualized operative planning. For example, AI-powered image segmentation tools could assist in defining dissection planes during TME, while augmented reality overlays may enable real-time navigation around pelvic autonomic nerves. Additionally, systems like Senhance® offering haptic feedback may enhance safety during LLND[40]. In parallel, standardized training programs incorporating dual-console systems, simulation-based curricula, and proficiency-based credentialing will be essential for the safe and efficient adoption of robotic technology.

Although the initial investment in robotic systems remains substantial, the potential benefits - including reduced conversion rates, improved functional outcomes, and shorter recovery - may offset costs in selected patient populations. Future research should focus on long-term oncologic and functional outcomes, cost-effectiveness, and patient-reported quality-of-life metrics to define the optimal role of RAS in contemporary rectal cancer management.

## CONCLUSIONS

RARCS constitutes a major advancement in minimally invasive colorectal surgery, offering distinct technological and clinical advantages over LAS. Accumulating evidence from RCTs, registry data, and meta-analyses supports the feasibility and safety of RARCS, demonstrating benefits in conversion rates, sphincter preservation, and nerve-sparing capabilities, particularly in technically demanding cases.

Although operative time is generally longer and cost remains a critical limitation, RARCS is associated with reduced intraoperative blood loss, favorable short-term recovery, and comparable or improved oncologic outcomes in selected patient populations. In particular, its ability to facilitate precise TME and preserve urogenital function underscores its potential to improve both oncologic radicality and postoperative quality of life.

Looking ahead, the integration of emerging technologies - such as alternative robotic platforms, AI, and augmented reality - combined with standardized training and credentialing, may accelerate the broader adoption and cost-effectiveness of RARCS. Continued high-quality research is warranted to validate long-term oncologic and functional outcomes, assess economic impact, and define patient-centered indications. As robotic platforms continue to evolve and become more accessible, RARCS is poised to play an increasingly central role in the modern surgical management of rectal cancer.

## DECLARATIONS

### Acknowledgments

The authors utilized Elicit and Consensus, an AI-powered research tool, to assist in the identification and selection of relevant literature during the early stages of this review. Additionally, ChatGPT (developed by OpenAI) was used for English language refinement and proofreading of the manuscript. All content was critically reviewed and edited by the authors to ensure accuracy, completeness, and originality.

### Authors' contributions

Contributed to the data collection, drafting of the manuscript, and development of the overall manuscript structure: Ueda K

Involved in organizing the manuscript content and performed critical revisions for important intellectual content: Iwamoto M, Tokoro T

Reviewed the manuscript for significant intellectual content and provided editorial feedback: Daito K, Yoshioka Y, Yane Y, Makutani Y, Haeno M, Umeda I

Supervised the overall project and approved the final version of the manuscript: Kawamura J, Gagner M

All authors have read and approved the final manuscript.

### Availability of data and materials

Not applicable.

**Financial support and sponsorship**

None.

**Conflicts of interest**

Gagner M is Honorary Editor-in-Chief of the journal *Mini-invasive Surgery*. Gagner M was not involved in any steps of editorial processing, notably including reviewer selection, manuscript handling, or decision making. The other authors declared that there are no conflicts of interest.

**Ethical approval and consent to participate**

Not applicable.

**Consent for publication**

Not applicable.



## REFERENCES

1. Kitano S, Inomata M, Mizusawa J, et al. Survival outcomes following laparoscopic versus open D3 dissection for stage II or III colon cancer (JCOG0404): a phase 3, randomised controlled trial. *Lancet Gastroenterol Hepatol.* 2017;2:261-8. DOI PubMed
2. Lacy AM, García-Valdecasas JC, Delgado S, et al. Laparoscopy-assisted colectomy versus open colectomy for treatment of non-metastatic colon cancer: a randomised trial. *Lancet.* 2002;359:2224-9. DOI PubMed
3. Clinical Outcomes of Surgical Therapy Study Group; Nelson H, Sargent DJ, Wieand HS, et al. A comparison of laparoscopically assisted and open colectomy for colon cancer. *N Engl J Med.* 2004;350:2050-9. DOI PubMed
4. Colon Cancer Laparoscopic or Open Resection Study Group; Buunen M, Veldkamp R, Hop WC, et al. Survival after laparoscopic surgery versus open surgery for colon cancer: long-term outcome of a randomised clinical trial. *Lancet Oncol.* 2009;10:44-52. DOI PubMed
5. Jayne DG, Guillou PJ, Thorpe H, et al; UK MRC CLASICC Trial Group. Randomized trial of laparoscopic-assisted resection of colorectal carcinoma: 3-year results of the UK MRC CLASICC Trial Group. *J Clin Oncol.* 2007;25:3061-8. DOI PubMed
6. Heald RJ, Ryall RD. Recurrence and survival after total mesorectal excision for rectal cancer. *Lancet.* 1986;1:1479-82. DOI PubMed
7. Gupta A, Dayal S, Moran BJ. Total mesorectal excision: embryology, anatomy, technique and outcomes. In: Kwaan M, Zbar A, editors. Comprehensive rectal cancer care. London: Springer Nature; 2019. pp. 125-46. DOI
8. Ballantyne GH, Moll F. The da Vinci telerobotic surgical system: the virtual operative field and telepresence surgery. *Surg Clin North Am.* 2003;83:1293-304, vii. DOI PubMed
9. Lee HJ, Choi GS, Park JS, et al. A novel robotic right colectomy for colon cancer via the suprapubic approach using the da Vinci Xi system: initial clinical experience. *Ann Surg Treat Res.* 2018;94:83-7. DOI PubMed PMC
10. Zihni AM, Ohu I, Cavallo JA, Cho S, Awad MM. Ergonomic analysis of robot-assisted and traditional laparoscopic procedures. *Surg Endosc.* 2014;28:3379-84. DOI PubMed
11. Sterne JAC, Savović J, Page MJ, et al. RoB 2: a revised tool for assessing risk of bias in randomised trials. *BMJ.* 2019;366:l4898. DOI PubMed
12. Shea BJ, Reeves BC, Wells G, et al. AMSTAR 2: a critical appraisal tool for systematic reviews that include randomised or non-randomised studies of healthcare interventions, or both. *BMJ.* 2017;358:j4008. DOI PubMed PMC
13. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ.* 2021;372:n71. DOI PubMed PMC
14. Jayne D, Pigazzi A, Marshall H, et al. Effect of robotic-assisted vs conventional laparoscopic surgery on risk of conversion to open laparotomy among patients undergoing resection for rectal cancer: the ROLARR randomized clinical trial. *JAMA.* 2017;318:1569-80. DOI PubMed PMC
15. Lanfranco AR, Castellanos AE, Desai JP, Meyers WC. Robotic surgery: a current perspective. *Ann Surg.* 2004;239:14-21. DOI PubMed PMC
16. Kwak JM, Kim SH. Robotic surgery for rectal cancer: an update in 2015. *Cancer Res Treat.* 2016;48:427-35. DOI PubMed PMC
17. Corrigan N, Marshall H, Croft J, Copeland J, Jayne D, Brown J. Exploring and adjusting for potential learning effects in ROLARR: a randomised controlled trial comparing robotic-assisted vs. standard laparoscopic surgery for rectal cancer resection. *Trials.* 2018;19:339. DOI PubMed PMC
18. Kim MJ, Park SC, Park JW, et al. Robot-assisted versus laparoscopic surgery for rectal cancer: a phase II open label prospective randomized controlled trial. *Ann Surg.* 2018;267:243-51. DOI PubMed

19. Feng Q, Yuan W, Li T, et al; REAL Study Group. Robotic versus laparoscopic surgery for middle and low rectal cancer (REAL): short-term outcomes of a multicentre randomised controlled trial. *Lancet Gastroenterol Hepatol.* 2022;7:991-1004. DOI PubMed
20. Xu J, Yuan W, Li T, et al. Robotic versus laparoscopic surgery for middle and low rectal cancer (REAL): primary outcome of a multicenter randomized controlled trial. *J Clin Oncol.* 2024;42:3617. DOI
21. Park JS, Lee SM, Choi GS, et al. Comparison of laparoscopic versus robot-assisted surgery for rectal cancers: the COLRAR randomized controlled trial. *Ann Surg.* 2023;278:31-8. DOI PubMed
22. Giesen LJX, Dekker JWT, Verseveld M, et al. Implementation of robotic rectal cancer surgery: a cross-sectional nationwide study. *Surg Endosc*. 2023;37:912-20. DOI PubMed PMC
23. Park EJ, Kim CW, Cho MS, et al. Multidimensional analyses of the learning curve of robotic low anterior resection for rectal cancer: 3-phase learning process comparison. *Surg Endosc.* 2014;28:2821-31. DOI PubMed
24. Ghadban T, Reeh M, Bockhorn M, et al. Minimally invasive surgery for colorectal cancer remains underutilized in Germany despite its nationwide application over the last decade. *Sci Rep.* 2018;8:15146. DOI PubMed PMC
25. Norwegian Institute of Public Health. Robotic surgery for rectal cancer: a health technology assessment. 2024. Available from: https://www.fhi.no/en/publ/2024/Robot-assisted-rectal-resection-for-rectal-cancer/. [Last accessed on 8 Jul 2025].
26. Duhoky R, Geitenbeek RTJ, Niccolò Piozzi G, et al. Ten years of robot-assisted versus laparoscopic total mesorectal excision for rectal cancer (short-term RESOLUTION). *J Natl Cancer Inst.* 2025:djaf084. DOI PubMed
27. Hamabe A, Takemasa I, Kotake M, et al. Feasibility of robotic-assisted surgery in advanced rectal cancer: a multicentre prospective phase II study (VITRUVIANO trial). *BJS Open.* 2024;8:zrae048. DOI PubMed PMC
28. Thrikandiyur A, Kourounis G, Tingle S, Thambi P. Robotic versus laparoscopic surgery for colorectal disease: a systematic review, meta-analysis and meta-regression of randomised controlled trials. *Ann R Coll Surg Engl.* 2024;106:658-71. DOI PubMed PMC
29. Zhang C, Tan H, Xu H, Ding J. The role of robotic-assisted surgery in the management of rectal cancer: a systematic review and meta-analysis. *Int J Surg.* 2024;110:6282-96. DOI PubMed PMC
30. Matsuyama T, Endo H, Yamamoto H, et al. Outcomes of robot-assisted versus conventional laparoscopic low anterior resection in patients with rectal cancer: propensity-matched analysis of the National Clinical Database in Japan. *BJS Open.* 2021;5:zrab083. DOI PubMed PMC
31. Takemasa I, Hamabe A, Sakamoto Y, et al. Japanese multicenter prospective study investigating laparoscopic surgery for locally advanced rectal cancer with evaluation of CRM and TME quality (PRODUCT trial). *Ann Gastroenterol Surg.* 2022;6:767-77. DOI PubMed PMC
32. de'Angelis N, Schena CA, Azzolina D, et al; Association Française de Chirurgie (AFC). Histopathological outcomes of transanal, robotic, open, and laparoscopic surgery for rectal cancer resection. A Bayesian network meta-analysis of randomized controlled trials. *Eur J Surg Oncol.* 2025;51:109481. DOI PubMed
33. Fleming CA, Cullinane C, Lynch N, Killeen S, Coffey JC, Peirce CB. Urogenital function following robotic and laparoscopic rectal cancer surgery: meta-analysis. *Br J Surg.* 2021;108:128-37. DOI PubMed
34. Duhoky R, Rutgers MLW, Burghgraef TA, et al. Long-term outcomes of robotic versus laparoscopic total mesorectal excisions: a propensity-score matched cohort study of 5-year survival outcomes. *Ann Surg Open.* 2024;5:e404. DOI PubMed PMC
35. Sakai Y, Morishita T. The financial impact of robotic surgery on hospital gross profits in Japan compared to laparoscopic surgery. *Asian J Endosc Surg.* 2025;18:e13410. DOI PubMed
36. Guerrero-Ortíz MA, Pellino G, Pascual Damieta M, et al; ROBOCOSTES Collaborative Group. Cost-effectiveness of robotic compared with laparoscopic rectal resection. Results from the Spanish prospective national trial ROBOCOSTES. *Surgery*. 2025;180:109134. DOI PubMed
37. Matsuyama T, Kinugasa Y, Nakajima Y, Kojima K. Robotic-assisted surgery for rectal cancer: current state and future perspective. *Ann Gastroenterol Surg.* 2018;2:406-12. DOI PubMed PMC
38. Mathew J, Bansod YK, Yadav N, et al. Laparoscopic versus robotic lateral pelvic lymph node dissection in locally-advanced rectal cancer: a cohort study comparing perioperative morbidity and short-term oncological outcomes. *Cancer Rep.* 2025;8:e70174. DOI PubMed PMC
39. Zhu H, Zou J, Pan H, Huang Y, Chi P. Comparison of laparoscopic versus robot-assisted sugery for rectal cancer after neo-adjuvant therapy: a large volume single center experience. *BMC Surg.* 2025;25:98. DOI PubMed PMC
40. Samalavicius NE, Dulskas A, Janusonis V, et al. Robotic colorectal surgery using the Senhance® robotic system: a single center experience. *Tech Coloproctol.* 2022;26:437-42. DOI PubMed