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Commentary

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Robotic-assisted surgery in colorectal cancer: clinical advantages, current limitations, and future perspectives

Davide Cavaliere, Marta Tanzanu, Sara Pellegrini, Francesco Pasini, Enrico Lazzarini, Benedetta Mattioli, Gianluca Senatore, Filippo Paratore

General Surgery, "Degli Infermi di Faenza" Hospital, AUSL della Romagna, Faenza 48018, Italy.

Correspondence to: Dr. Davide Cavaliere, General Surgery, "Degli Infermi di Faenza" Hospital, AUSL della Romagna, Faenza 48018, Italy. E-mail: cavalied@gmail.com

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Abstract

Robotic-assisted surgery represents a significant advancement in minimally invasive colorectal cancer (CRC) surgery, providing enhanced precision, superior visualization, and potentially improved oncological outcomes compared to laparoscopy. These benefits are particularly significant in low rectal cancer, characterized by narrow pelvic anatomy and critical autonomic nerve preservation. Nonetheless, challenges such as increased operative times, high costs, and extensive training requirements hinder broader adoption. This commentary reviews clinical advantages, current limitations, and future perspectives of robotic colorectal surgery, aiming to inform colorectal surgeons and healthcare stakeholders on the evolving role of robotics in CRC treatment.

Keywords: Robotic surgery, colorectal cancer, minimally invasive surgery, cost-effectiveness, learning curve, surgical outcomes

INTRODUCTION

Colorectal cancer (CRC) is the third most diagnosed malignancy and the second leading cause of cancer-related mortality worldwide, with an estimated 1.93 million new cases and over 1 million deaths reported in 2022[1]. The global burden of CRC is projected to rise, partly due to aging populations, changes in lifestyle habits, and increased detection rates. Developed countries continue to bear the highest incidence, but rising trends are being observed in low- and middle-income nations, particularly among younger adults.

In response to the rising incidence, surgical management remains the cornerstone of curative CRC treatment. The evolution from open surgery to minimally invasive techniques, notably laparoscopy, has significantly improved postoperative recovery, reduced complication rates, and enhanced patient satisfaction[2]. However, limitations of conventional laparoscopy - such as restricted instrument motion and two-dimensional imaging - can pose challenges, especially in complex pelvic procedures. Due to these limiting factors, the penetration of laparoscopy in colorectal surgery remains low[3].

Robotic-assisted surgery (RAS) was developed to overcome these constraints, enabling more precise dissection, improved ergonomics, and superior intraoperative control. Despite these technical advances, RAS implementation has been uneven, with adoption affected by factors such as institutional resources, learning curve dynamics, and cost-efficiency concerns.

CLINICAL ADVANTAGES

Until a few years ago, only one robotic platform was available in clinical practice - the da Vinci system by Intuitive. Over the course of approximately three decades, it evolved through four generations, each offering enhanced performance, instrumentation, and software capabilities. The scientific literature has predominantly been shaped by experiences with this platform. Only in recent years have competing manufacturers introduced robotic surgical systems for colorectal procedures; however, literature on these newer platforms remains limited. Nevertheless, available data reinforce the clinical value of RAS in colorectal surgery. The multicenter REAL trial by Feng *et al.*, involving 1,171 patients, reported that robotic surgery significantly reduced intraoperative blood loss, decreased complication rates, lowered the need for conversion to open surgery, shortened hospital stays, and improved oncological metrics such as lymph node retrieval and mesorectal excision quality[4]. These findings confirm that RAS offers tangible benefits, particularly in rectal cancer cases requiring intricate pelvic maneuvers.

Complementary evidence from a recent systematic review and meta-analysis of randomized controlled trials by Zou *et al.* (2025) further underscores the advantages of RAS. The analysis demonstrated earlier restoration of urinary and gastrointestinal functions, fewer postoperative complications, and lower conversion rates compared to laparoscopy[5]. These improvements translate into shorter recovery times and improved perioperative outcomes, enhancing patient experience and reducing healthcare utilization.

Moreover, novel robotic platforms are contributing to diversification in surgical performance. Hugo™ (Medtronic) and Versius® (CMR Surgical) have shown clinical equivalence to the Da Vinci system in early clinical experience/comparative cohorts. Hugo™ demonstrated effective outcomes and notably faster docking times, contributing to more efficient OR turnover[6]. Versius® has been validated in colorectal settings, showing favorable results regarding blood loss, operative time, and complication rates in both single-center and multicenter studies[7,8]. These emerging platforms are designed to improve accessibility by lowering costs and increasing modularity, offering more tailored solutions for diverse surgical environments.

At present, there is insufficient consolidated evidence to allow a precise comparison of docking time, instrument flexibility, and modular designs across robotic platforms.

However, Table 1 summarizes the current evidence and available comparisons among different platforms in colorectal surgery.

Further multicenter studies are required to clarify the relative advantages of each system, particularly in complex procedures.

ONCOLOGICAL OUTCOMES OF RAS

RAS in CRC continues to demonstrate favorable oncological outcomes, particularly in total mesorectal excision (TME) quality and functional preservation. The landmark Robotic *vs.* Laparoscopic Resection for Rectal Cancer (ROLARR) randomized controlled trial[9] comparing robotic and laparoscopic rectal resections (n = 471) revealed similar completeness of TME (76.4% *vs.* 77.6%) and circumferential resection margin (CRM) positivity rates (6.3% for laparoscopy *vs.* 5.1% for robotics, P = 0.56), with a trend toward lower conversion rates in male patients (8.1% *vs.* 12.2%, P = 0.16)[9]. Although not statistically significant, these findings underscore the potential advantages of RAS in anatomically complex cases.

A subsequent multicenter randomized controlled trial [comparison of laparoscopic versus robot-assisted surgery for rectal cancer (COLRAR), n = 295] confirmed similar TME completeness (80.7% *vs.* 77.1%, P-value non statistically significant) but noted a significantly lower positive CRM rate in the robotic arm (0% *vs.* 6.1%, P-value non statistically significant), as well as reduced opioid use postoperatively (P = 0.028)[10]. These findings indicate improved precision and functional outcomes in robotic procedures.

Further meta-analyses strengthen this evidence. A comprehensive recent review of 11 RCTs (n = 3,107) demonstrated robotic superiority in several oncological metrics: a markedly lower conversion rate [odds ratio (OR) 0.42, 95% confidence interval (CI) 0.28-0.63, P < 0.0001], fewer positive CRMs (OR 0.59, 95%CI 0.41-0.85, P = 0.004), and increased lymph node retrieval (+0.67 nodes, P = 0.0004)[5]. The same analysis observed faster postoperative recovery without compromising short-term morbidity or mortality.

Real-world data also reinforce these advantages. A multicenter Indian registry (n = 829) reported lower CRM positivity in robotic cases compared to laparoscopic and open surgery, along with reduced blood loss, fewer complications, and comparable long-term survival at 5 years (92.3% *vs.* 90.5% for laparoscopy, P = 0.12)[11]. Additionally, a recent cohort study (n = 526) confirmed similar margin negativity (~2.1%) and long-term survival outcomes among robotic, laparoscopic, and open approaches, with robotic surgery showing reduced perioperative morbidity[12].

Despite these encouraging results, long-term oncological outcomes continue to evolve. A recent study suggests comparable 5-year overall survival rates between robotic and laparoscopic TME, although larger-scale studies are needed[13].

Similarly, the recent prospective randomized REAL trial reports comparable 3-year overall survival between robotic and laparoscopic treatment of mid- and low-rectal cancer. However, the same study suggests an advantage for the robotic group in terms of 3-year locoregional recurrence and disease-free survival. With longer follow-up, larger cohorts, and refinement of surgical expertise, these findings may be confirmed or even further strengthened over time[14].

LIMITATIONS AND COST-EFFECTIVENESS OF ROBOTIC COLORECTAL SURGERY

Despite clear clinical benefits, the high financial burden associated with RAS remains a major obstacle to its

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Table 1. Comparison of robotic surgery platforms for CRC

Platform	Claim	Evidence summary	Study type /level	Year	Journal	DOI	PMID	Link
Da Vinci (Xi/4th gen)	RCT shows no significant reduction in conversion *vs.* laparoscopy for rectal cancer; oncologic outcomes comparable	ROLARR: 471 patients; no significant difference in conversion, CRM+, complications, or QoL[9]	Randomized controlled trial (Level 1)	2017	*JAMA*	10.1001/jama.2017.7219	29067426	https://pubmed.ncbi.nlm.nih.gov/29067426/
Da Vinci (Xi vs Si)	Xi improves OR efficiency (operative time, docking, LOS) with similar safety/oncology to Si	Systematic review/meta-analysis of 8 studies (~1,000 pts): Xi -26.9 min OT, -4.2 min docking, -0.98 days LOS; no difference in complications/conversion[33]	Systematic review & meta-analysis (Level 1)	2025	*Journal of Robotic Surgery*	10.1007/s11701-025-02466-3	40580391	https://pubmed.ncbi.nlm.nih.gov/40580391/
Hugo™ RAS (Medtronic)	Perioperative and oncologic outcomes comparable to laparoscopy in CRC, even early in the learning curve	Retrospective single-center comparative cohort (*n* = 109): no difference in complications, time, conversion, LOS, R0, nodes, TME/CRM quality[6]	Comparative cohort (Level 2-3)	2025	*Cancers (Basel)*	10.3390/cancers17071164	40227728	https://pubmed.ncbi.nlm.nih.gov/40227728/
Hugo™ RAS (Medtronic)	Feasibility and safety in colorectal surgery during initial adoption	Early single-center series in colorectal disease; platform with modular arms and open console[34]	Case series (Level 4)	2024	*Int J Colorectal Dis*	10.1007/s00384-024-04715-7	39289218	https://link.springer.com/article/10.1007/s00384-024-04715-7
Versius® (CMR Surgical)	Prospective multicenter registry demonstrates safe implementation; includes colorectal cases	First analysis of the Versius Surgical Registry: 2,083 cases with low complication/90-day mortality; includes 162 anterior resections[35]	Prospective registry (IDEAL stage 3)	2023	*Annals of Surgery*	10.1097/SLA.0000000000005871	37036097	https://journals.lww.com/annalsofsurgery/fulltext/2023/10000/safe_implementation_of_a_next_generation_surgical.53.aspx
Versius® (CMR Surgical)	Evidence in CRC is growing; comparative data still limited	2025 systematic review of Versius in colorectal surgery[8]	Systematic review (Level 1)	2025	*Journal of Robotic Surgery*	10.1007/s11701-025-02336-y	40295444	https://pubmed.ncbi.nlm.nih.gov/40295444/

CRC: Colorectal cancer; RCT: ROLARR: Robotic *vs.* Laparoscopic Resection for Rectal Cancer; CRM: circumferential resection margin; QoL: quality of life; OR: operative room; LOS: lenght of stay; OT: operative time; TME: total mesorectal excision.

widespread adoption. Studies have consistently shown that robotic colorectal procedures come with significantly higher direct and overall costs compared to laparoscopic approaches. A large-scale U.S. inpatient database analysis reported that robotic-assisted colorectal resections in 2014 resulted in an increase of approximately $5,272 in total and $4,432 in direct costs ($P < 0.001$), in addition to a median operative time increase of 39 min[15]. Similarly, Simianu *et al.* (2020) modeled 1-year costs and quality-adjusted life years (QALYs), finding that robotic colectomy incurred an incremental cost of $745 per case[16]. Other decision-analytic evaluations corroborate that, although both robotic and laparoscopic colectomies are cost-effective relative to open surgery, laparoscopy remains the preferred option under standard willingness-to-pay benchmarks, and robotic procedures only become economically viable under very specific cost or time reductions.

Moreover, robotic rectal surgery - while offering superior functional outcomes such as improved nerve preservation - follows the same cost trend: significant increases in capital amortization, instrument maintenance, and operative time compared to laparoscopy. The short-term clinical gains do not yet justify the long-term investment, particularly when durability of oncologic outcomes is still to be fully confirmed[17].

Nonetheless, economies of scale and institutional optimization can partially offset these costs. High-volume robotic centers can distribute fixed capital investments over larger caseloads, maximize instrument reuse protocols, and achieve efficiencies in surgical workflow, potentially mitigating per-case expenditure. Sensitivity analyses indicate that modest cost reductions - such as a $400 decrease per disposable set or a 20-minute reduction in operative time - could shift the cost-benefit balance in favor of RAS, especially in rectal operations where quality-of-life benefits are most pronounced[18].

The above does not consider regional heterogeneity in cost-effectiveness. In resource-constrained settings such as India, Brazil, and parts of Southeast Asia, several strategies have been adopted to mitigate the high costs of robotic surgery. These include alternative procurement models such as leasing or pay-per-use contracts, centralization of procedures in high-volume referral centers, and in some cases the acquisition of refurbished systems or newer platforms with lower capital investment. Corporate social responsibility (CSR) initiatives and selective public funding have also supported access in specific hospitals, while shared-use arrangements among institutions have been reported. In addition, operational optimization, including reduced turnover times and standardized workflows, has been emphasized to maximize utilization and reduce per-case costs. Nevertheless, reimbursement policies remain highly heterogeneous across regions, and robust economic data on the long-term sustainability of these strategies are still limited[19,20].

It is beyond our aim to provide an exhaustive economic analysis, and our discussion does not fully capture the heterogeneity of healthcare systems and cost-effectiveness across different regions, particularly in low- and middle-income countries, where direct knowledge of system functioning is limited.

Future investigations should therefore adopt a multidisciplinary approach, involving health economists and regional stakeholders, to more comprehensively assess procurement models, reimbursement strategies, and long-term sustainability.

LEARNING CURVE AND TRAINING IN ROBOTIC COLORECTAL SURGERY

Mastering robotic colorectal surgery requires a structured learning pathway, as surgeon proficiency evolves through distinct phases. CUSUM (cumulative sum) analyses from multiple centers reveal that robotic right colectomy proficiency typically emerges after 25-30 cases, while TME, especially rectal resections, often requires 40-60 cases of experience to achieve consistent operative performance[21-24].

Simulation-based training and virtual reality modules significantly accelerate early skill acquisition by reducing errors and standardizing exposure before live surgery. A prospective study of 141 robotic colorectal cases with enhanced recovery showed operative efficiency stabilizing after roughly 31 cases, with full-team proficiency achieved by 60 cases, critical for workflow and patient outcomes[25].

Institutional implementations increasingly rely on modular, structured curricula endorsed by surgical societies. Training pathways typically progress from didactic fundamentals and simulation to proctored bedside roles and ultimately surgeon console autonomy[26].

These frameworks include clear criteria for progression, competency milestones, and defined training durations. The European Society of Coloproctology and national bodies recommend such multi-phase, assessment-based programs to ensure safe and effective adoption.

Despite progress, variations in learning milestones persist due to factors such as baseline laparoscopic expertise, case complexity, faculty mentorship, and institutional volume[21]. Continuous credentialing with performance benchmarks - based on metrics such as docking time, console duration, complication rates, and nerve preservation - is critical to maintaining quality standards as robotic case numbers grow.

FUTURE PERSPECTIVES OF ROBOTIC COLORECTAL SURGERY

The horizon of robotic-assisted colorectal surgery is marked by rapid technological convergence:

1. Single-Port Robotics: The da Vinci SP™ system offers three-wristed instruments and a three-dimensional (3D) high-definition (HD) endoscope through a single small incision. Early feasibility/clinical studies reported in a scoping review demonstrate its safety and feasibility in colorectal resections, with early oncological and perioperative outcomes showing parity or improvement versus multi-port methods[27].

2. AI-Enhanced Systems: Present artificial intelligence (AI)-driven systems incorporate functionalities such as image recognition, motion control, and haptic feedback, allowing real-time analysis of surgical field images and optimizing instrument movements for surgeons[28].

3. Augmented Reality (AR) Integration: AR overlays - integrating preoperative imaging directly into the surgical field - have been linked to reduced visual distraction, better situational awareness, and improved precision, especially during oncologic dissections[29].

4. SemiAutonomous Functionality: Emergent systems feature context-aware assistance, including automatic tool tracking, suturing support, and safety alerts. While these innovations promise enhanced efficiency, they also introduce ethical and regulatory challenges around accountability, patient privacy, and physician oversight[30].

These advancements suggest a future in which robotic surgery becomes more intelligent, efficient, and accessible. However, implementation will rely on robust validation, clear regulatory frameworks, and updated ethical guidelines to ensure patient safety and public trust.

POLICY IMPLICATIONS AND STRATEGIC RECOMMENDATIONS

From a policy perspective, governments and healthcare systems must take a proactive role in supporting the responsible and equitable integration of RAS into CRC treatment frameworks.

1. Centralize Services in High-Volume Centers. Public investment should prioritize equipping high-volume cancer centers and academic hospitals with next-generation robotic platforms, as these environments maximize clinical outcomes, research productivity, and cost efficiency. Centralized care models have been shown to improve procedural standardization, reduce conversion rates, and yield better postoperative outcomes. For instance, the Dutch Colorectal Audit reported a national increase from 15% to 22% in robotic-assisted resections; this group saw consistently lower conversion rates and maintained quality benchmarks across nearly 6,300 procedures[31].

2. Adopt Outcome-Based Reimbursement. Healthcare payers should shift toward value-based reimbursement models that incentivize not just volume, but superior clinical and functional outcomes. Policies that reward successful nerve-sparing, low conversion rates, shorter hospital stays, and patient-reported quality of life measures can justify RAS's higher upfront costs and incentivize data-driven adoption.

3. Develop Cross-Sector Collaborations. Effective implementation requires partnerships among health ministries, regulatory authorities, academic centers, and industry. These collaborations should aim to negotiate transparent cost structures, enable bulk procurement or leasing models, and extend RAS access to smaller or rural hospitals. In parallel, standardized curricula and accredited fellowships - endorsed by professional bodies - are essential. The 2024 robotic training guideline of the European Society of Coloproctology emphasizes the need for uniform credentialing and structured robotic curricula across Europe[32].

4. Embed RAS in National Cancer Frameworks. Policymakers should integrate robotic surgery into national cancer control plans, especially for tumor types such as low rectal cancer where RAS offers distinct anatomical and functional benefits. Inclusion in quality indicators and national registries will facilitate benchmarking, outcome tracking, and iterative improvement.

5. Ensure Equitable Access. Targeted programs designed to deploy RAS in underserved regions - through tele-mentoring, remote proctoring, and mobile surgical units - can mitigate geographic disparities. Public-private partnerships and international development funding can accelerate outreach, particularly in lower-resource settings.

CONCLUSION

RAS is poised to play an increasingly prominent role in the management of CRC. Its demonstrated clinical benefits, combined with ongoing innovations in AI, AR, and platform design, hold promise for more efficient and precise surgical care. However, challenges related to cost, training, and long-term outcomes remain. Investments in training infrastructure, reimbursement policy, and multidisciplinary collaboration are essential to foster equitable access and ensure safe implementation.

Finally, strategic policy engagement, financial innovation, and multisectoral coordination are key to translating RAS advancements into population-level health improvements. By embedding robotic platforms within broader health system reforms and clinical governance structures, robotic colorectal surgery can evolve from an elite innovation to a universally accessible standard of care.

DECLARATIONS

Authors' contributions

Conceptualization: Cavaliere D
Methodology: Cavaliere D
Investigation: Cavaliere D, Tanzanu M
Writing - original draft preparation: Cavaliere D, Tanzanu M
Writing - review and editing: Lazzarini E, Pasini F, Pellegrini S, Mattioli B, Paratore F, Senatore G
Supervision: Cavaliere D
All authors approved the final version of the manuscript.

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Cavaliere D has a consulting contract for proctoring activities in robotic surgery within the field of general surgery with a supplier/distributor of robotic platforms for soft-tissue surgery. He also serves as an Editorial Board Member of *Mini-invasive Surgery* and as a Guest Editor for the topic "Robotic-Assisted Colorectal Cancer Resection". Cavaliere D was not involved in any part of the editorial process for this manuscript, including reviewer selection, manuscript handling, or decision-making. The other authors declare that they have no conflicts of interest.

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Not applicable.

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