Augmented Reality and Three-Dimensional Technologies in Colorectal Surgery: Current Applications and Future Perspectives. A Narrative Review.

Abstract

Introduction:
Recent advances in augmented reality (AR) and three-dimensional (3D) technologies have created new opportunities to improve visualization, preoperative planning, and intraoperative decision-making in colorectal surgery.

Objective:
To provide a comprehensive overview of the current evidence regarding the clinical applications of augmented reality and three-dimensional technologies in colorectal surgery.

Materials and Methods:
A narrative review of the literature was performed through a structured search of PubMed/MEDLINE and Scopus, including studies evaluating the use of AR and 3D technologies in colorectal surgical practice.

Results:
Current evidence indicates that these technologies may enhance anatomical visualization, facilitate individualized surgical planning, improve intraoperative spatial orientation, and contribute to surgical education and technical skill development.

Conclusion:
Augmented reality and three-dimensional technologies have considerable potential as adjunctive tools in colorectal surgery. Nevertheless, further high-quality clinical studies are required to confirm their effectiveness and support their widespread integration into routine surgical practice.

Keywords

Colorectal surgery; surgical planning; augmented reality; three-dimensional printing; colorectal oncology.

Introduction

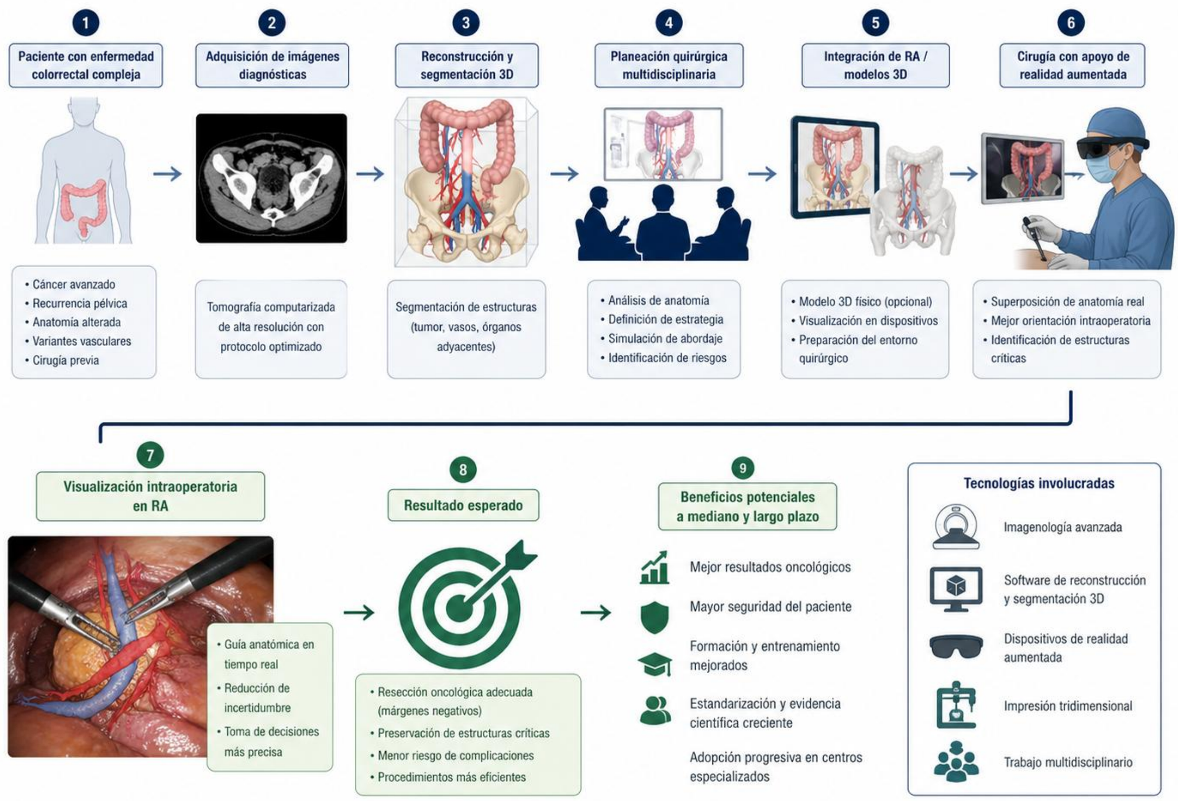
Modern colorectal surgery has undergone remarkable advances over the past decades with the widespread adoption of laparoscopic techniques, robotic-assisted surgery, and the standardization of oncologic surgical principles. Despite these developments, colorectal procedures continue to pose significant technical challenges because of the complex retroperitoneal anatomy, mesenteric vascular variability, limited pelvic workspace, and the need to achieve oncologically sound resections while preserving critical anatomical structures.[1–3]

Conventional preoperative planning is primarily based on two-dimensional imaging modalities, including computed tomography (CT) and magnetic resonance imaging (MRI), which remain the standard for anatomical assessment and tumor staging. However, these techniques have inherent limitations in representing complex three-dimensional anatomical relationships, particularly in patients with locally advanced malignancies, vascular anatomical variants, and deep pelvic disease. In this setting, augmented reality (AR) and three-dimensional (3D) technologies have emerged as promising adjuncts for improving anatomical visualization, optimizing surgical planning, and enhancing operative training. These technologies encompass three-dimensional digital reconstruction, 3D printing, and the integration of virtual anatomical information into the surgical field, allowing more accurate visualization of vascular anatomy and tumor relationships.[1,2,8] **Figure 1** illustrates the principal potential applications of these technologies in colorectal surgery.

Although the available evidence in colorectal surgery remains limited and heterogeneous, encouraging results have been reported in complex right hemicolectomy, complete mesocolic excision, advanced rectal surgery, and the localization of difficult colorectal lesions.[1,2,6,7,10,11] Furthermore, experience from hepatobiliary surgery and the management of complex pelvic tumors suggests that these technologies may improve individualized surgical planning and intraoperative anatomical orientation.[4,5]

Despite these promising developments, important challenges remain regarding cost-effectiveness, accessibility, and their actual impact on clinical outcomes, particularly in healthcare systems with limited or variable resources, such as those in Mexico and other Latin American countries. The aim of this narrative review is to summarize the current evidence regarding the application of augmented reality and three-dimensional technologies in colorectal surgery, with particular emphasis on surgical safety, oncologic planning, and surgical training, while discussing their current limitations and future perspectives.

Figura 1. Algoritmo de implementación clínica de la realidad aumentada y tecnologías tridimensionales en cirugía colorrectal



RA: realidad aumentada; 3D: tridimensional.

Materials and Methods

A structured narrative review was conducted to evaluate the available scientific evidence regarding the application of augmented reality (AR) and three-dimensional (3D) technologies in colorectal surgery.

A comprehensive literature search was performed using the PubMed/MEDLINE and Scopus databases. The search was supplemented by manual screening of the reference lists of relevant publications and an additional search in Google Scholar. Studies published between January 2010 and March 2026 were considered, with particular emphasis on evidence generated during the last five years.

The search strategy included combinations of the following English-language keywords: *augmented reality*, *mixed reality*, *three-dimensional reconstruction*, *3D printing*, *colorectal surgery*, *colon cancer*, *rectal cancer*, *surgical planning*, *laparoscopy*, and *surgical training*.

Eligible publications included original research articles, systematic reviews, prospective studies, pilot studies, case series, and technical reports describing the clinical, educational, or preoperative planning applications of AR and 3D technologies in colorectal surgery. In addition, selected studies from related surgical fields, including hepatobiliary surgery and the management of complex pelvic tumors, were incorporated when they described technologies with potential applicability to colorectal surgical practice.[4,5]

Conference abstracts without full-text availability, duplicate publications, experimental studies lacking direct clinical applicability, and articles not relevant to the objectives of this review were excluded.

The final selection prioritized studies according to methodological quality, clinical relevance, recency of publication, and potential applicability to colorectal surgery. The principal characteristics of the studies included in the qualitative narrative synthesis are summarized in **Table 1**.

Table 1. Main Characteristics of the Studies Included on Augmented Reality and Three-Dimensional Technologies in Colorectal Surgery

Author / Year	Study Design	Area of Interest	Technology	Main Findings
Bracale et al., 2024	Narrative review with preliminary clinical experience	Colorectal surgery	Mixed reality	Improved preoperative planning and anatomical orientation in complex colorectal procedures.
Habermann et al., 2024	Systematic review	Colorectal surgery	Three-dimensional (3D) printing	Useful for surgical education, preoperative planning, and lesion localization; however, current clinical evidence remains limited.
Jerí-McFarlane et al., 2024	Prospective non-randomized protocol	Locally advance	Three-dimensional (3D) reconstruction	Potential to optimize individualized surgical planning and facilitate complete oncologic resection.
Oshiro et al., 2017	Applied clinical study	Hepatobiliary surgery	Three-dimensional simulation and 3D printing	Improved vascular understanding and preoperative planning for complex hepatobiliary procedures.
Ivanov et al., 2024	Clinical case series	Complex pelvic tumors	Augmented reality	Enhanced tumor orientation and visualization of relationships with adjacent anatomical structures.
Fletcher et al., 2025	Observational study	Right hemicolectomy	Three-dimensional (3D) reconstruction	Improved anatomical and vascular understanding during complete mesocolic excision.
Huber et al., 2019	Technical report with clinical experience	Rectal surgery	Mixed reality	Demonstrated potential utility during robotic surgery and transanal approaches by improving intraoperative orientation.
Ryu et al., 2022	Comparative study	Complex colorectal surgery	Mixed reality versus 3D reconstruction	Improved spatial perception and intraoperative guidance in complex colorectal procedures.
Nepal et al., 2021	Observational study	Left-sided colon surgery	Three-dimensional CT angiography	Facilitated identification of vascular anatomical variants for safer preoperative planning.
Luzon et al., 2020	Applied anatomical study	Right hemicolectomy	Three-dimensional vascular modeling	Supported central vascular dissection and D3 lymphadenectomy through improved vascular visualization.
Soriero et al., 2022	Clinical case series	Complex colorectal lesions	Three-dimensional models	Improved lesion localization and segmental surgical planning in selected colorectal cases.

Surgical Safety

Surgical safety is one of the principal drivers behind the adoption of augmented reality (AR) and three-dimensional (3D) technologies in colorectal surgery. Minimally invasive colorectal procedures, particularly laparoscopic and robotic approaches, require meticulous dissection within confined anatomical spaces while preserving major vascular, neural, and urological structures. Improved preoperative anatomical visualization may therefore reduce intraoperative uncertainty and contribute to safer surgical decision-making.[1,2]

Right hemicolectomy with complete mesocolic excision represents one of the clinical scenarios in which these technologies appear to offer the greatest benefit. Anatomical variations involving the middle colic artery, middle colic vein, and the gastrocolic trunk of Henle frequently complicate central vascular dissection. Bracale et al. demonstrated that three-dimensional reconstruction enables accurate preoperative identification of these vascular variants, thereby facilitating operative planning and surgical strategy.[1] Similarly, Fletcher et al. reported improved anatomical understanding and vascular orientation during right hemicolectomy using patient-specific three-dimensional reconstructions.[6]

For left-sided colectomy and rectal surgery, preoperative visualization of the inferior mesenteric vessels and adjacent retroperitoneal structures may assist in safer vascular ligation while reducing the risk of ureteral injury. Nepal et al. described the usefulness of three-dimensional CT angiography for tailoring the surgical approach in left-sided colorectal resections according to individual vascular anatomy.[9] In complex rectal surgery, Huber et al. suggested that mixed reality technology may improve intraoperative spatial orientation during transanal and robotic procedures, facilitating navigation within the narrow pelvic cavity.[7]

In patients with locally advanced colon cancer, Jerí-McFarlane et al. proposed that three-dimensional reconstruction may improve tumor delineation and support planning of extended oncologic resections.[3] Comparable experiences from hepatobiliary surgery and the treatment of complex pelvic tumors further support the potential value of AR and 3D technologies in anatomically demanding operations.[4,5]

Despite these encouraging findings, the current body of evidence remains limited and is largely derived from pilot studies, small case series, and single-center experiences. Consequently, the most consistently demonstrated benefit of these technologies is the enhancement of anatomical understanding and preoperative planning, whereas definitive improvements in operative time, complication rates, or other major clinical outcomes have yet to be established.[1,2]

Oncologic Applications

Colorectal oncologic surgery requires meticulous preoperative planning to achieve complete tumor resection, adequate surgical margins, and appropriate lymphovascular dissection in accordance with current oncologic principles. In this setting, augmented reality (AR) and three-dimensional (3D) technologies may provide important advantages by improving anatomical assessment and supporting individualized surgical strategies for complex cases.[1,2]

One of the most promising areas of application is the management of locally advanced colon cancer. In patients with suspected invasion of adjacent organs or close proximity to retroperitoneal structures, conventional imaging may be insufficient to accurately define the extent of disease and the optimal surgical approach. Jerí-McFarlane et al. proposed a three-dimensional reconstruction protocol to enhance tumor visualization and facilitate preoperative planning, with the goal of increasing the likelihood of complete (R0) oncologic resections.[3]

Rectal cancer surgery presents additional challenges because of the confined pelvic anatomy and the need to obtain negative circumferential resection margins while preserving adjacent neurovascular and urogenital structures. Bracale et al. reported early clinical experience suggesting that mixed reality technology improves the spatial understanding of the relationship between the tumor, mesorectum, and surrounding organs, particularly in patients with a narrow pelvis or those undergoing advanced minimally invasive procedures.[1] Likewise, Huber et al. described the potential utility of these technologies during robotic and transanal mesorectal surgery by enhancing intraoperative anatomical orientation.[7]

Three-dimensional technologies may also assist in the localization of difficult colorectal lesions, including small tumors, post-polypectomy lesions, and lesions located within anatomically distorted bowel segments. Soriero et al. suggested that patient-specific 3D models can improve segmental orientation and facilitate surgical planning in selected colorectal cases.[11]

Beyond colorectal surgery, evidence from the management of primary and recurrent pelvic malignancies further supports the potential value of AR-guided surgical navigation. Ivanov et al. demonstrated that augmented reality may improve intraoperative anatomical orientation and visualization of the relationship between tumors and adjacent pelvic structures during complex oncologic resections.[5] These findings may have future implications for locally recurrent rectal cancer and other locally invasive colorectal malignancies.

Nevertheless, the available evidence remains limited and heterogeneous. To date, the principal reported benefits involve improved preoperative planning and enhanced understanding of tumor anatomy, whereas the impact of these technologies on long-term oncologic outcomes—including overall survival, local recurrence, and disease-free survival—has yet to be established through well-designed prospective clinical studies.[1,2]

Advanced Anatomical Understanding

A thorough understanding of anatomy is fundamental to successful colorectal surgery, particularly during minimally invasive procedures in which tactile feedback is limited and spatial orientation relies primarily on visual information. In this context, augmented reality (AR) and three-dimensional (3D) technologies allow conventional radiologic images to be converted into intuitive anatomical models, facilitating the interpretation of complex spatial relationships before and during surgery.[1,2]

One of the most valuable applications of these technologies involves mesenteric vascular anatomy. Considerable anatomical variability exists in the middle colic artery and vein, the gastrocolic trunk of Henle, and the superior mesenteric vascular axis, making central vascular ligation during right hemicolectomy with complete mesocolic excision technically demanding. Bracale et al. demonstrated that patient-specific 3D reconstructions improve preoperative identification of these vascular structures, enabling a more individualized and accurate surgical approach.[1] Likewise, Fletcher et al. reported educational and anatomical benefits associated with the use of three-dimensional models during right-sided colorectal surgery.[6]

In left-sided colectomy and sigmoid surgery, detailed visualization of the inferior mesenteric artery and vein, together with their relationship to the left ureter and adjacent retroperitoneal structures, may further enhance operative planning. Nepal et al. showed that three-dimensional CT angiography facilitates the identification of vascular variants and supports safer preoperative assessment for laparoscopic left-sided colorectal resections.[9]

The deep pelvis represents another anatomically demanding region in colorectal surgery. Total mesorectal excision requires meticulous dissection in close proximity to the autonomic pelvic plexus, ureters, and adjacent pelvic organs. In these complex procedures, three-dimensional reconstruction and mixed reality technologies may improve spatial perception and facilitate recognition of intricate anatomical planes. Early clinical experiences reported by Bracale et al. and Huber et al. suggest that these technologies can enhance anatomical orientation during advanced rectal surgery and transanal minimally invasive approaches.[1,7]

Beyond direct clinical applications, AR and 3D technologies may reduce the cognitive demands associated with mentally reconstructing three-dimensional anatomy from conventional two-dimensional imaging. Interactive virtual models enable surgeons to examine vascular and tumor relationships from multiple perspectives, supporting more informed decision-making and more precise operative planning.[2,11]

Nevertheless, the clinical usefulness of these technologies depends on several factors, including the quality of radiologic image segmentation, the anatomical accuracy of the reconstructed model, and the surgical team's ability to correctly interpret and integrate this information into operative planning. Consequently, although AR and 3D technologies represent promising tools for improving advanced anatomical understanding, they should be considered complementary to—rather than a replacement for—comprehensive surgical anatomical knowledge.[1,2]

Surgical Training and Education

Contemporary surgical education faces the challenge of developing technical proficiency and advanced anatomical knowledge while maintaining high standards of patient safety in increasingly complex operative environments. In this context, augmented reality (AR) and three-dimensional (3D) technologies have emerged as promising educational tools capable of complementing traditional training methods in colorectal surgery.[1,2]

One of the principal advantages of these technologies is their ability to enhance preoperative anatomical understanding. Patient-specific three-dimensional models enable surgical trainees to visualize vascular anatomy, mesenteric planes, and complex anatomical relationships more effectively than conventional two-dimensional imaging. Bracale et al. summarized early experiences demonstrating that these technologies improve preoperative preparation and spatial orientation during technically demanding colorectal procedures.[1]

In right-sided colon surgery, Fletcher et al. reported that three-dimensional reconstruction improved anatomical and vascular understanding during right hemicolectomy with complete mesocolic excision, particularly among less experienced surgeons.[6] These findings suggest that patient-specific 3D visualization may facilitate the learning process and help shorten the learning curve for procedures characterized by considerable anatomical variability.

Advanced rectal surgery represents another area in which AR and 3D technologies may contribute to surgical education. Three-dimensional reconstruction and mixed reality platforms can be incorporated into preoperative simulation and team preparation for technically demanding procedures, including laparoscopic, robotic, and transanal total mesorectal excision. Huber et al. described the potential role of these technologies in improving operative planning and enhancing surgical team readiness before complex pelvic interventions.[7]

Patient-specific three-dimensional printed models constitute an additional educational resource. In their systematic review, Habermann et al. reported that these models have been successfully used to improve anatomical understanding, facilitate discussion of complex clinical cases, and support preoperative simulation.[2] They may also serve as valuable teaching tools during academic conferences, resident training sessions, multidisciplinary planning meetings, and patient education.

Despite their potential, AR and 3D technologies should not be regarded as substitutes for conventional surgical education based on anatomical knowledge, supervised operative experience, and progressive clinical decision-making. Rather, they should be viewed as complementary educational resources that enhance visualization and technical preparation, particularly for complex or infrequently performed procedures. Further prospective studies are required to determine their impact on knowledge acquisition, technical performance, learning curves, and clinical outcomes.[1,2]

Feasibility, Costs, and Clinical Implementation

Despite the growing interest in augmented reality (AR) and three-dimensional (3D) technologies for colorectal surgery, their widespread clinical adoption remains limited by economic, logistical, and organizational challenges. Most published studies originate from academic or high-volume tertiary centers with access to advanced technological infrastructure, which may restrict the generalizability of their findings to institutions with fewer resources.[1,2]

The initial investment required for implementation may include image-segmentation software, high-performance workstations, three-dimensional printers, and, in selected cases, augmented or mixed reality platforms. In addition, the creation of patient-specific anatomical models requires dedicated time for image processing, anatomical validation, and multidisciplinary collaboration among surgeons, radiologists, and biomedical engineers. These requirements may hinder routine implementation outside specialized centers.[2]

However, not all applications require substantial financial investment. Digital three-dimensional reconstruction generated from conventional computed tomography images represents a more accessible alternative than the immediate adoption of sophisticated AR hardware. Bracale et al. emphasized that the current value of these technologies lies primarily in improving preoperative planning rather than advanced intraoperative navigation.[1] This observation suggests that a stepwise implementation strategy may be more feasible than introducing a comprehensive technological platform from the outset.

Within colorectal surgery, selective application in technically demanding cases is likely to provide the greatest cost-benefit ratio. Potential indications include locally advanced colon cancer, right hemicolectomy with complex mesenteric vascular anatomy, difficult pelvic dissections, locally recurrent rectal cancer, and reoperative colorectal procedures. Jerí-McFarlane et al. proposed the use of three-dimensional reconstruction as a personalized planning tool for patients with locally advanced colon cancer.[3]

In healthcare systems such as those in Mexico and other Latin American countries, adoption will probably occur gradually and unevenly. High-volume referral centers, university hospitals, and specialized colorectal units are likely to represent the most appropriate settings for the initial validation and implementation of these technologies. At the same time, three-dimensional printed models and virtual reconstructions may play an important role in surgical education, simulation, and advanced training programs.[2]

Beyond financial considerations, successful implementation also requires adequate personnel training, multidisciplinary collaboration, and objective evaluation of clinical outcomes. The incorporation of new technologies without clearly defined clinical indications may increase healthcare costs without providing measurable patient benefit. Therefore, the current evidence supports a selective and purpose-driven implementation of AR and 3D technologies, particularly when they are used to enhance surgical safety, optimize oncologic planning, or improve surgical education and training.[1,2]

The principal advantages, limitations, and potential clinical applications of these technologies are summarized in **Table 2**.

Table 2. Advantages, Limitations, and Potential Applications of Augmented Reality and Three-Dimensional Technologies in Colorectal Surgery

Application Area	Potential Advantages	Current Limitations	Most Likely Clinical Applications
Surgical Safety	Improved anatomical orientation, enhanced vascular identification, and reduced intraoperative uncertainty.	Limited clinical evidence, learning curve, and dependence on advanced technology.	Complex colorectal procedures and advanced minimally invasive surgery.
Colorectal Oncology	Personalized surgical planning, improved tumor assessment, and support for achieving R0 resection.	Insufficient evidence regarding survival, recurrence, and long-term oncologic outcomes.	Locally advanced colorectal cancer and locally recurrent pelvic disease.
Advanced Anatomical Understanding	Three-dimensional visualization of vascular variants and complex spatial relationships.	Requires high-quality imaging, accurate segmentation, and validated reconstruction models.	Right hemicolectomy with complete mesocolic excision and complex pelvic surgery.
Surgical Training and Education	Enhanced anatomical teaching, preoperative simulation, and support during the surgical learning curve.	Variable availability, implementation costs, and lack of standardized educational evidence.	Surgical residency programs, fellowships, and advanced colorectal training.
Institutional Feasibility	Progressive implementation and selective use in referral centers according to clinical complexity.	Initial costs, unequal technological infrastructure, and need for multidisciplinary support.	University hospitals, tertiary referral centers, and high-volume colorectal units.
Future Perspectives	Integration with artificial intelligence, workflow automation, image-guided navigation, and precision surgery.	Need for multicenter validation, cost-effectiveness analyses, and standardized clinical protocols.	Gradual incorporation into specialized healthcare systems and precision colorectal surgery programs.

Current Limitations of the Available Evidence

Despite the growing interest in augmented reality (AR) and three-dimensional (3D) technologies for colorectal surgery, the available evidence remains limited and heterogeneous. Most published studies consist of case series, pilot studies, institutional experiences, technical reports, or narrative reviews, generally involving small patient cohorts and variable study methodologies.[1,2] Consequently, the current literature does not yet provide sufficient evidence to draw definitive conclusions regarding the clinical effectiveness of these technologies.

A major limitation is the scarcity of well-designed prospective comparative studies evaluating clinically meaningful outcomes, such as reductions in major postoperative complications, intraoperative blood loss, conversion to open surgery, length of hospital stay, or improvements in oncologic outcomes. Instead, many studies primarily report subjective endpoints, including enhanced anatomical understanding, increased surgeon confidence, or user satisfaction, which provide lower levels of clinical evidence.[1,2]

Another important challenge is the considerable heterogeneity among the technologies evaluated. The term "three-dimensional technologies" encompasses a broad spectrum of applications, including digital 3D reconstruction, three-dimensional printing, augmented reality, mixed reality, and image-guided navigation systems, each with different levels of technological sophistication and clinical implementation. This diversity complicates direct comparisons between studies and limits the ability to perform meaningful evidence synthesis.[1]

Institutional selection bias also represents a significant limitation. Most available evidence originates from high-volume academic referral centers with extensive experience in minimally invasive colorectal surgery, advanced imaging capabilities, and multidisciplinary collaboration involving radiologists and biomedical engineers. As a result, the reported outcomes may not be readily reproducible in hospitals with lower surgical volumes or more limited technological resources.[2,3]

Furthermore, relatively little information is available regarding cost-effectiveness, image-processing time, implementation logistics, learning curves, or long-term operational sustainability. These factors are particularly relevant in healthcare systems with constrained financial resources, where the adoption of new technologies requires clear demonstration of measurable clinical benefits.[2]

Finally, the effectiveness of AR and 3D technologies depends heavily on the quality of preoperative imaging, the accuracy of anatomical segmentation, and the surgical team's ability to correctly interpret and integrate these models into clinical decision-making. Therefore, although the preliminary evidence is encouraging, additional prospective, multicenter, comparative studies with objective clinical endpoints are necessary to better define the true role of these technologies in colorectal surgery and to support their routine clinical implementation.[1,2]

Conclusions

Augmented reality (AR) and three-dimensional (3D) technologies represent promising innovations in the evolution of contemporary colorectal surgery. The available evidence suggests potential benefits in anatomical understanding, preoperative planning, surgical safety, oncologic management, and surgical education, particularly in technically demanding procedures.[1,2]

However, the current literature remains limited and heterogeneous, and routine implementation of these technologies cannot yet be universally recommended. At present, their use appears to be most appropriate in experienced centers, selected complex cases, and academic institutions with established expertise in minimally invasive colorectal surgery and surgical innovation.[1,3]

Worldwide implementation is expected to occur gradually as technological accessibility improves, image-processing workflows become more efficient, and clinical experience continues to expand. In the near term, patient-specific three-dimensional reconstruction, virtual surgical planning, and three-dimensional printed models are likely to represent the most feasible and widely adopted applications before advanced intraoperative navigation systems become routinely available.

High-quality prospective multicenter studies with objective clinical endpoints and cost-effectiveness analyses are still needed to better define the role of these technologies in colorectal surgery. Until stronger evidence becomes available, AR and 3D technologies should be regarded as complementary tools that enhance—but do not replace—sound surgical judgment, technical expertise, and comprehensive anatomical knowledge.

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