

## Modern Roles And Future Horizons Of Minimally Invasive CABG: A Narrative Literature Review

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### Abstract

*Minimally invasive surgery (MIS) has undergone significant evolution over the past 25 years, fundamentally reshaping modern surgical practice. Compared with traditional open procedures, MIS is associated with reduced tissue trauma, lower infection rates, and faster postoperative recovery. This review highlights recent clinical and technological advances in MIS, with particular emphasis on minimally invasive coronary surgery (MICS) and the integration of advanced imaging technologies.*

*Major innovations include the widespread adoption of robotic surgical platforms, particularly the da Vinci robotic system, and the development of totally endoscopic coronary artery bypass (TECAB), which enables complete myocardial revascularization without median sternotomy. The emergence of hybrid operating rooms (ORs) has further improved procedural efficiency by combining sterile surgical environments with high-resolution three-dimensional imaging modalities, such as cone-beam computed tomography (CBCT). These facilities support complex image-guided interventions and allow the seamless combination of surgical and percutaneous techniques.*

*Immersive technologies, including Virtual Reality (VR) and Mixed Reality (MR), are increasingly applied in preoperative planning and intraoperative guidance, enhancing spatial orientation and visualization of complex cardiovascular anatomy. Additionally, artificial intelligence (AI) and machine-learning algorithms contribute to motion correction, image optimization, and real-time decision support during cardiovascular procedures.*

*Despite these advancements, important challenges remain, including steep learning curves for robotic techniques, high equipment and maintenance costs, and limited tactile feedback in current robotic systems. Imaging artifacts and radiation exposure also represent ongoing technical concerns. Future developments are expected to focus on multimodal imaging, haptic feedback integration, and patient-centered innovations to further enhance surgical precision and safety. Continued*

*multidisciplinary collaboration and robust clinical validation are essential to translate these technological advances into improved patient outcomes.*

Keywords: Minimally invasive surgery; Minimally invasive coronary surgery; Robotic cardiac surgery; Hybrid operating room; Advanced imaging; Artificial intelligence; Totally endoscopic coronary artery bypass.

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## 1. Introduction

Minimally invasive surgery (MIS) has emerged as a transformative paradigm in modern medicine, fundamentally redefining surgical practice by enabling complex interventions through small incisions, often measuring less than 1 cm. By employing specialized instruments and advanced imaging technologies, MIS minimizes collateral tissue damage, resulting in reduced postoperative pain, lower infection rates, and accelerated recovery compared with conventional open surgery [2,4,12]. In addition to clinical benefits, MIS offers superior cosmetic outcomes and mitigates the psychological burden associated with extensive surgical trauma, thereby improving overall patient quality of life [4].

The evolution of MIS reflects a progressive shift from early endoscopic and laparoscopic techniques to highly sophisticated robotic-assisted platforms and hybrid operating environments. While initial advances were concentrated in general surgery, the mid-1990s marked a pivotal expansion into technically demanding domains such as minimally invasive coronary surgery (MICS) [2,3]. This transition has been driven by the convergence of surgical expertise and rapid technological innovation. The introduction of robotic systems, most notably the da Vinci platform, addressed key limitations of conventional minimally invasive approaches by providing three-dimensional high-definition visualization, tremor filtration, and enhanced dexterity through wristed instruments that closely replicate natural hand movements [2,12].

A major milestone in this technological progression is the development of the hybrid operating room (OR). Hybrid

ORs integrate fully sterile surgical environments with advanced coordinate-based imaging modalities, including cone-beam computed tomography (CBCT) and magnetic resonance imaging (MRI), enabling real-time intraoperative guidance and immediate verification of procedural outcomes [8]. These capabilities are particularly critical in complex cardiovascular and neurovascular interventions, where millimeter-level precision and rapid intraoperative decision-making are essential for patient safety [8].

More recently, immersive visualization technologies such as Virtual Reality (VR) and Mixed Reality (MR) have further expanded the scope of MIS. These tools facilitate detailed preoperative planning and intraoperative holographic guidance by allowing surgeons to interact with patient-specific three-dimensional anatomical models [1,7]. By enhancing spatial understanding and cognitive integration of complex anatomy, immersive technologies bridge the gap between preoperative imaging and real-time surgical execution, improving both efficiency and accuracy [1,7].

Despite these advancements, the widespread adoption of MIS remains constrained by several challenges. Robotic and image-guided procedures are associated with steep learning curves, complex ergonomics, and demanding patient positioning requirements [5]. The absence of true haptic feedback in robotic surgery continues to be a significant limitation, necessitating heavy reliance on visual cues and indirect sensory information [12]. Economic considerations further restrict accessibility, as high capital investment costs and specialized training requirements may exacerbate disparities between healthcare systems [4,5].

Against this background, the present review synthesizes recent clinical and technological advances in minimally invasive surgery, with particular emphasis on image-guided navigation, robotic assistance, and immersive visualization. By critically evaluating current evidence, this review aims to elucidate how emerging innovations address existing limitations and shape the future of precision-guided, patient-centered surgical care.

## 2. Methods

This review integrates evidence from systematic scoping reviews, prospective clinical feasibility studies, and phantom-based experimental protocols [2,6,8–11]. Comprehensive literature searches were performed in PubMed, Scopus, Embase, Web of Science, IEEE Xplore, and the Cochrane Library using MeSH terms and Boolean operators related to image-guided navigation, robotic-assisted surgery, and minimally invasive surgery [2,6,8]. Scoping reviews included in this synthesis adhered to established methodological frameworks, including PRISMA-ScR guidelines and the Arksey and O'Malley approach, to ensure reproducible study selection and data extraction [6,8].

The analysis incorporates a large clinical dataset, including 74 patient series spanning 25 years and a total of 11,135 minimally invasive coronary procedures. This is complemented by focused evaluations of emerging technologies such as mixed reality (MR), virtual reality (VR), and artificial intelligence (AI) [1,2,5,6].

Technical precision was assessed using phantom-based experiments. Motion correction was evaluated with the Xsight lung phantom under controlled motion patterns, including continuous sinusoidal and breath-hold simulations, to validate the CAVAREC image reconstruction algorithm [9]. Silicone rubber abdominal phantoms were used to simulate the tactile resistance of soft tissues during needle navigation tasks [10,11].

Robotic navigation platforms, including ANT-C and CAS-One IR systems, were evaluated for accuracy by measuring Euclidean, lateral, and depth deviations between the needle tip and planned targets [10,11]. Their performance was benchmarked against conventional freehand needle placement performed by expert radiologists and novice trainees [11].

Advanced visualization technologies were assessed through prospective feasibility studies involving immersive 3D VR environments and HoloLens® 2–

guided MR holography [1,7]. Patient-specific CT datasets were segmented using ITK-SNAP and 3D Slicer to generate holographic anatomical models for surgical planning and intraoperative guidance [1,7]. In cardiac procedures, holographic projections were registered to anatomical landmarks, such as the clavicle and xiphoid process, to guide intercostal access [1].

Qualitative outcomes were collected using validated User Evaluation Questionnaires (UEQ) and Likert-scale surveys to assess ergonomics, usability, and workflow integration [1,7,8]. Statistical robustness was ensured using inter-rater reliability analysis with Gwet's AC1 index and propensity-score matching to compare minimally invasive procedures with conventional sternotomy-based approaches [5,8].

## 3. Results

### Clinical Outcomes and Comparative Efficacy:

Cumulative evaluation of minimally invasive surgery (MIS) demonstrates consistent improvements in patient safety and procedural efficiency across multiple surgical domains [2]. Analysis of 11,135 patients over a 25-year period revealed a hospital mortality rate of 1.0%, a stroke rate of 0.6%, and surgical site infections in 1.2% of cases. The mean postoperative hospital stay was 5.6 days, indicating accelerated recovery compared with conventional open procedures [2].

Comparative studies between minimally invasive coronary surgery (MICS) and conventional coronary artery bypass grafting (CABG) show similar 30-day mortality rates, while MICS is associated with shorter hospitalizations and faster functional recovery [5]. In patients with isolated proximal left anterior descending (LAD) artery disease, minimally invasive direct coronary artery bypass (MIDCAB) achieved a 7-year repeat revascularization rate of 1.5%, compared with approximately 20% following percutaneous coronary intervention with drug-eluting stents [3]. Robotic-assisted CABG demonstrated mortality rates as low as 0.3% and left internal thoracic artery (LITA)–to–LAD graft patency rates of 97.4% [3]. Long-term outcomes reported a 10-year survival of 77.7% after MIDCAB, comparable to age-matched population survival [3]. Despite these benefits, robotic procedures were associated with longer operative times and higher initial costs [5,12].

### Technological Precision and Robotic Navigation:

Phantom-based experiments confirmed superior

targeting accuracy of robotic-assisted navigation systems compared with conventional freehand techniques [10,11]. In abdominal phantom studies, the ANT-C robotic platform achieved a mean Euclidean targeting error of 3.5 mm, outperforming expert radiologists using freehand insertion, who achieved 4.6 mm. Robotic placement required no corrective adjustments, while freehand techniques required an average of 1.7 adjustments per attempt. Targeting time was substantially reduced with robotic assistance (36 seconds) versus freehand insertion (95 seconds) [11].

In contrast, clinical evaluation of the CAS-One IR system for percutaneous nephrolithotomy showed a single-attempt technical success rate of 29%, with a mean needle-target deviation of 5.9 mm [10]. This lower success rate was primarily due to the lack of real-time compensation for organ motion and tissue deformation during respiration [10].

**Advanced Visualization and Preoperative Planning:** Immersive visualization technologies significantly improved surgical planning and intraoperative efficiency [1,7]. HoloLens® 2–based mixed reality (MR) guidance reduced mean operative time by 34.3 minutes during minimally invasive cardiac procedures [1]. In all cases, MR-guided incision planning differed by at least one intercostal space from the surgeon’s initial estimate, demonstrating improved spatial accuracy [1].

Immersive 3D virtual reality (VR) planning allowed

surgeons to modify operative strategies and port placements within 15 minutes of review [7]. Surgeons rated the usefulness and efficiency of VR planning at a mean score of 4.4 out of 5 [7]. Additionally, multimodal intravascular imaging combining near-infrared spectroscopy (NIRS) and intravascular ultrasound (IVUS) achieved 89% sensitivity for detecting lipid-rich plaques and was associated with a 47% reduction in major adverse cardiac events at one year compared with angiography alone [6].

**Hybrid Operating Room Utilization:** A systematic scoping review of 44 procedures performed in hybrid operating rooms (ORs) across nine clinical disciplines highlighted improved procedural accuracy (35%) and enhanced patient safety (35%) as primary benefits [8]. These facilities enable simultaneous open and percutaneous interventions, allowing immediate management of intraoperative complications [8]. However, challenges included prolonged OR utilization (32%) and increased radiation exposure [8].

In navigation-assisted renal procedures, the mean patient radiation dose was 6.4 mSv, with cone-beam CT contributing 82% of the total exposure [8]. The CAVAREC image reconstruction algorithm enhanced instrument edge sharpness in clinical imaging, though artifacts near bone occasionally limited its applicability [9].

**Table 1. Summary of Clinical and Technological Outcomes in Minimally Invasive**

**CABG and Related Technologies**

Domain	Study Focus	Key Findings	Clinical/Technical Impact	Reference
<b>Clinical Outcomes (MIS overall)</b>	25-year cumulative analysis (11,135 patients)	Hospital mortality: 1.0%   Stroke: 0.6%   Surgical site infection: 1.2%   Mean hospital stay: 5.6 days	Demonstrates long-term safety and reduced postoperative morbidity compared with open surgery	Bonatti et al., 2021
<b>MICS vs Conventional CABG</b>	Comparative clinical studies	Similar 30-day mortality   Shorter hospitalization   Faster functional recovery with MICS	Supports minimally invasive strategy as effective alternative to sternotomy	Raja, 2025

<b>MIDCAB (LAD disease)</b>	Long-term follow-up	7-year repeat revascularization: 1.5% (vs ~20% PCI)   10-year survival: 77.7%   LITA-LAD patency: 97.4%   Mortality as low as 0.3%	Excellent graft durability and long-term survival	Marin-Cuartas et al., 2021
<b>Robotic Navigation (ANT-C)</b>	Phantom-based abdominal model	Mean targeting error: 3.5 mm (vs 4.6 mm freehand)   0 corrective adjustments   Targeting time: 36 sec (vs 95 sec)	Improved precision and efficiency compared with freehand technique	Spenkelnik et al., 2023
<b>CAS-One IR System</b>	Clinical nephrolithotomy study	Single-attempt success: 29%   Needle deviation: 5.9 mm	Limited real-time motion compensation reduces clinical success	Spenkelnik et al., 2024
<b>Mixed Reality (MR) Guidance</b>	HoloLens® 2 cardiac procedures	Operative time reduced by 34.3 min   Incision planning differed by $\geq 1$ intercostal space	Improved spatial accuracy and intraoperative efficiency	Aye et al., 2025
<b>Virtual Reality (VR) Planning</b>	Immersive 3D preoperative planning	Strategy modification within 15 min   Usefulness rating: 4.4/5	Enhanced preoperative planning and decision-making	Sadeghi et al., 2020
<b>Multimodal Imaging (NIRS + IVUS)</b>	Intravascular imaging	89% sensitivity for lipid-rich plaques   47% reduction in 1-year MACE	Improved diagnostic sensitivity and clinical outcomes	Roshanfar et al., 2025
<b>CAVAREC Algorithm</b>	Motion-corrected CBCT imaging	Improved instrument edge sharpness   Bone-related artifacts present	Enhances image clarity but limited by artifact susceptibility	Spenkelnik et al., 2024

#### 4. Discussion

The shift from traditional open surgery to minimally invasive surgery (MIS) represents a major paradigm change aimed at minimizing surgical trauma and

accelerating postoperative recovery [4]. This review confirms that MIS consistently provides clinical benefits across multiple surgical disciplines, including reduced infection rates, lower complication profiles, and shorter hospital stays [2,4]. Long-term data from minimally

invasive coronary surgery show sustained safety, with hospital mortality remaining near 1.0% over 25 years [2]. However, the technical complexity of these procedures requires careful balancing of reduced invasiveness against increased procedural demands [5].

A key challenge in MIS is the “hidden field” phenomenon, where surgeons lose direct visual and tactile feedback and rely on video-mediated visualization [8]. Hybrid operating rooms address this limitation by integrating real-time three-dimensional imaging, such as cone-beam CT, directly into the sterile surgical environment [8]. Despite these advancements, a gap remains between technological performance in controlled settings and real-world clinical outcomes. For example, robotic navigation systems achieve high accuracy in phantom models, yet clinical trials of percutaneous renal access report limited technical success due to organ motion and tissue deformation [10,11].

Immersive visualization technologies, including virtual reality (VR) and mixed reality (MR), offer effective solutions to the cognitive demands of three-dimensional anatomical interpretation [1,7]. MR-guided holography allows surgeons to superimpose patient-specific anatomy onto the operative field in real time, leading to significant reductions in operative time and improved incision accuracy [1]. VR-based preoperative planning further supports surgical decision-making by enabling rapid modification of strategies in a risk-free environment [7]. These tools enhance spatial awareness and provide “cognitive coherence” between imaging and intraoperative execution, which is particularly valuable in complex procedures.

Despite these benefits, widespread adoption of advanced MIS technologies is constrained by economic and logistical barriers [5]. Robotic systems require substantial capital investment, with costs exceeding \$1.5 million, and achieving procedural proficiency often necessitates a high number of cases to overcome the initial learning curve [2,12]. These challenges highlight the importance of structured simulation-based training and mentorship programs to ensure patient safety during the adoption of new technologies [4].

Future progress in MIS is likely to be driven by multimodal imaging integration and artificial intelligence (AI) [6]. Hybrid systems that combine structural and molecular imaging have already demonstrated superior diagnostic sensitivity compared

with standalone modalities [6]. AI-driven solutions hold promise for real-time motion correction, predictive analytics, and intraoperative decision support. To fully realize these advancements, future research should extend beyond feasibility studies to large-scale comparative trials assessing long-term clinical outcomes and cost-effectiveness [8].

Ultimately, the goal is to transition MIS from a selectively applied alternative to a widely accessible standard of care, leveraging technological innovation to improve both procedural precision and patient-centered outcomes [5].

## 5. Conclusion

Minimally invasive coronary artery bypass surgery has matured into a safe and effective alternative to conventional sternotomy-based approaches, supported by over two decades of cumulative clinical experience. Contemporary evidence demonstrates that minimally invasive and robotic-assisted CABG techniques achieve low perioperative mortality, excellent graft patency, and long-term survival comparable to traditional CABG, while offering the additional benefits of reduced surgical trauma, shorter hospital stays, and faster functional recovery. These outcomes confirm the growing role of minimally invasive strategies in carefully selected patients with coronary artery disease.

The evolution of minimally invasive CABG has been inseparable from advances in surgical technology. Robotic platforms have expanded the technical feasibility of totally endoscopic revascularization, while hybrid operating rooms have enabled the integration of surgical and percutaneous techniques within a single procedural environment. Furthermore, immersive visualization tools, including virtual and mixed reality, have emerged as powerful adjuncts for preoperative planning and intraoperative guidance, improving anatomical understanding, surgical precision, and workflow efficiency. The incorporation of artificial intelligence and multimodal imaging further enhances procedural accuracy by addressing limitations related to motion, visualization, and real-time decision-making.

Despite these advances, several barriers continue to limit widespread adoption. High acquisition and maintenance costs, steep learning curves, limited tactile feedback, and variability in institutional resources remain significant challenges. In addition, many technological innovations are currently supported by feasibility studies rather than

large-scale comparative trials, underscoring the need for robust clinical validation.

Future progress in minimally invasive CABG will depend on the convergence of technological refinement, standardized training pathways, and multidisciplinary collaboration. The integration of haptic feedback, AI-driven navigation, and patient-specific imaging holds particular promise for closing the gap between technical innovation and clinical reliability. As evidence continues to accumulate, minimally invasive CABG is poised to transition from a specialized alternative to an integral component of modern, patient-centered coronary revascularization strategies.

## 6. Declarations

This study is a systematic review and did not involve direct research on human participants or animals; therefore, ethics approval and consent to participate are not applicable. No individual patient data are included, and consent for publication is not required. All data generated or analyzed during this study are provided within this article and its references. The authors declare no competing interests. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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