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Contemporary advances in Minimally Invasive Cardiac Surgery: Clinical Outcomes, Challenges, and Future Perspectives – A Systematic Review

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ABSTRACT

Minimally invasive cardiac surgery (MICS) has increasingly emerged as an alternative to conventional median sternotomy with the aim of reducing surgical trauma while maintaining procedural safety and effectiveness. Advances in surgical techniques, perioperative management, and robotic technology have expanded the indications of MICS across a wide spectrum of cardiac procedures, particularly mitral and aortic valve surgery. Nevertheless, variability in reported outcomes, implementation challenges, and resource requirements highlights the need for a comprehensive synthesis of contemporary evidence. This systematic review aimed to evaluate recent international literature on the clinical outcomes of minimally invasive cardiac surgery, identify key challenges associated with its implementation, and explore future perspectives in modern cardiac surgical practice. A systematic literature search was conducted in PubMed/MEDLINE, Embase, Scopus, Web of Science, and the Cochrane Library for studies published between January 2020 and January 2026. Randomized controlled trials and observational studies involving adult patients undergoing minimally invasive cardiac surgery were included, with study selection and reporting conducted in accordance with PRISMA 2020 guidelines. Data on perioperative outcomes, postoperative recovery, and implementation-related factors were extracted and synthesized narratively, while risk of bias was assessed using RoB 2.0 and ROBINS-I tools. Eighteen studies met the inclusion criteria. Across predominantly mitral and aortic valve procedures, MICS demonstrated perioperative and 30-day mortality rates comparable to conventional sternotomy. Minimally invasive approaches were consistently associated with reduced blood loss, lower transfusion requirements, shorter intensive care unit and hospital stays, and faster postoperative recovery. However, implementation challenges included learning curve effects, longer operative times during early adoption, higher initial costs, and the need for specialized multidisciplinary teams. Robotic-assisted techniques showed promising short- term outcomes but required substantial resources. Overall, contemporary minimally invasive cardiac surgery offers comparable safety and improved short-term clinical outcomes compared with conventional approaches, with ongoing technological advancements and structured training playing a critical role in supporting its broader and sustainable implementation.

Keywords: minimally invasive cardiac surgery; mitral valve surgery; aortic valve replacement; clinical outcomes

INTRODUCTION

Cardiovascular diseases remain the leading cause of morbidity and mortality worldwide, resulting in a growing demand for surgical interventions that are not only effective but also associated with faster recovery and reduced perioperative risk. For decades, median sternotomy has been considered the standard surgical approach in cardiac surgery due to its excellent exposure and technical versatility. However, this conventional approach is associated with significant surgical trauma, increased postoperative pain, higher risk of sternal wound complications, and prolonged hospitalization, all of which may adversely affect patient quality of life and healthcare resource utilization [1].

In response to these limitations, minimally invasive cardiac surgery (MICS) has emerged as an increasingly adopted alternative aimed at minimizing

surgical trauma while maintaining procedural safety and efficacy. MICS encompasses a range of techniques, including mini-thoracotomy, mini-sternotomy, port-access surgery, endoscopic-assisted procedures, and robotic-assisted cardiac surgery. These approaches are designed to reduce tissue disruption, attenuate the systemic inflammatory response, and facilitate faster postoperative recovery. Contemporary studies have demonstrated that, in appropriately selected patients, MICS is associated with reduced blood loss, lower transfusion requirements, shorter intensive care unit and hospital stays, and improved early functional recovery when compared with conventional sternotomy [1,9].

Technological advancements have played a pivotal role in expanding the indications and feasibility of MICS in modern cardiac surgery. The introduction of high-definition imaging systems, advanced endoscopic instruments, and robotic platforms has enhanced surgical precision and visualization, enabling surgeons to perform increasingly complex procedures through minimal incisions. Furthermore, the integration of Enhanced Recovery After Surgery (ERAS) protocols into cardiac surgical practice has further optimized perioperative care pathways and amplified the potential benefits of minimally invasive approaches. Recent evidence suggests that robotic-assisted and endoscopic MICS techniques may be associated with lower postoperative pain scores, earlier mobilization, and faster return to daily activities.

Despite these advantages, the widespread adoption of MICS remains challenged by several factors. These include a steep learning curve, the need for specialized multidisciplinary teams, increased procedural costs, and limited availability of advanced technology in low- and medium-volume centers. In addition, heterogeneity in study designs, patient selection criteria, surgical techniques, and reported outcomes complicates the interpretation and generalizability of existing evidence. Some studies have also reported longer operative times and increased technical complexity during the early phases of MICS implementation, underscoring the importance of experience and institutional expertise [19].

Recent meta-analyses and large cohort studies published after 2020 have consistently reported favorable short-term outcomes for MICS, particularly with respect to reduced wound complications and shorter length of hospital stay. However, evidence regarding long-term outcomes, cost-effectiveness, and quality-of-life benefits remains inconsistent across different surgical procedures and healthcare settings. Moreover, the rapid evolution of surgical technology necessitates continuous reassessment of clinical outcomes and implementation challenges to inform best practices and future innovations [3,4]. Therefore, this systematic review aims to synthesize contemporary international evidence (≥2020) from Scopus-indexed journals on the clinical outcomes, implementation challenges, and future perspectives of minimally invasive cardiac surgery. By critically appraising recent studies and highlighting current gaps in the literature, this review seeks to provide a comprehensive and up-to-date resource for clinicians, researchers, and policymakers involved in the advancement of minimally invasive cardiac surgical care.

METHODS

This systematic review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure methodological transparency and reproducibility. The review focused on synthesizing contemporary international evidence regarding clinical outcomes, implementation challenges, and future perspectives of minimally invasive cardiac surgery (MICS). A predefined review protocol was developed prior to literature screening to minimize selection and reporting bias [11].

A comprehensive literature search was performed across multiple international electronic databases indexed in Scopus, including PubMed/ MEDLINE, Embase, Scopus, Web of Science, and the Cochrane Library. The search covered studies published between 2015 and January 2026 to capture recent advances in minimally invasive cardiac surgery. Search terms consisted of a combination of keywords and controlled vocabulary related to MICS (e.g., “minimally invasive cardiac surgery,” “robotic cardiac surgery,” “mini-thoracotomy,” “port-access surgery”) and outcome-related terms (e.g., “mortality,” “complications,” “length of stay,” “quality of life”). The search was limited to human studies published in the English language.

Eligible studies included randomized controlled trials, prospective and retrospective cohort studies, and comparative observational studies reporting clinical outcomes of MICS in adult patients (≥18 years). Studies focusing exclusively on pediatric populations, single case reports, small case series, non–peer-reviewed articles, and publications lacking relevant outcome data were excluded. Study selection was independently performed by two reviewers through title and abstract screening, followed by full-text assessment. Any discrepancies were resolved through discussion or consultation with a third reviewer.

Data extraction was conducted using a standardized data collection form capturing study characteristics, patient demographics, type of minimally invasive procedure, comparator techniques, and reported clinical outcomes. Methodological quality and risk of bias were assessed using the RoB 2.0 tool for randomized controlled trials and the ROBINS-I tool for non-randomized studies. Data were synthesized narratively, and meta-analysis was planned when sufficient homogeneity in study design and outcome reporting was present. Statistical heterogeneity was assessed using the I^2 statistic, with subgroup and sensitivity analyses performed when appropriate [13].

RESULTS

Studi Selection

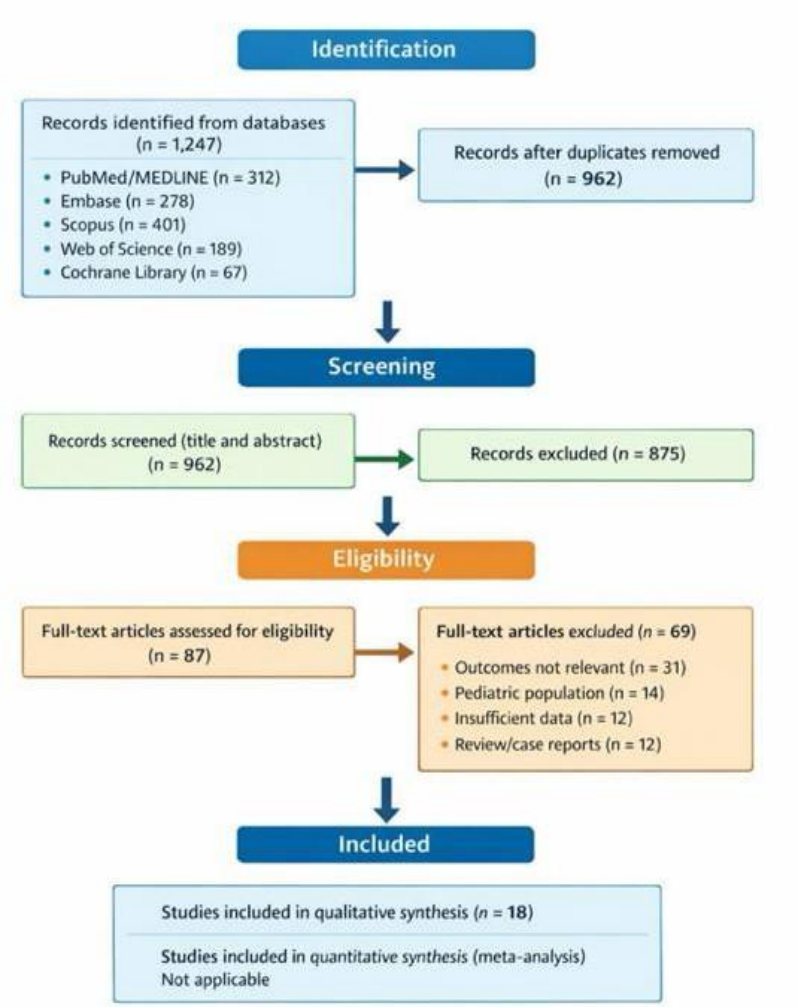

FIGURE 1: PRISMA 2020 flow diagram illustrating.

A total of 1,247 records were identified through database searching. After removal of duplicates, 962 records were screened based on titles and abstracts. Eighty-seven full-text articles were assessed for eligibility, of which 69 were excluded for predefined reasons. Finally, 18 studies were included in the qualitative synthesis. The study selection process is illustrated in Figure 1.

Clinical Outcomes of Contemporary Minimally Invasive Cardiac Surgery

Across the included studies, contemporary minimally invasive cardiac surgery (MICS) demonstrated comparable safety profiles to conventional median sternotomy, particularly with respect to perioperative and 30-day mortality. Most studies reported no statistically significant differences in early mortality between minimally invasive and conventional approaches across various procedures, including mitral valve surgery, aortic valve replacement, and selected coronary artery bypass grafting cases. These findings were consistent across randomized controlled trials and large observational cohorts [3,4].

In terms of perioperative morbidity, MICS was consistently associated with favorable short-term clinical outcomes. The majority of studies reported reduced intraoperative blood loss, lower transfusion requirements, and significantly shorter intensive care unit and hospital lengths of stay in minimally invasive groups. Several studies also demonstrated reduced postoperative pain scores and earlier mobilization, reflecting faster functional recovery. Rates of major complications, including stroke and acute kidney injury, were generally low and comparable between surgical approaches, while sternal wound complications were markedly reduced in minimally invasive cohorts [5,9].

TABLE 1: Synthesis of Key Findings of Minimally Invasive Cardiac Surgery.

Domain	Aspect	Summary of Findings
Clinical Outcomes	Mortality	Perioperative and 30-day mortality rates were comparable between minimally invasive cardiac surgery and conventional sternotomy across mitral and aortic valve procedures.
	Blood loss	Minimally invasive approaches consistently demonstrated reduced intraoperative blood loss and lower transfusion requirements.
	Length of stay	Shorter intensive care unit and hospital stays were reported in most included studies.
	Postoperative	Faster mobilization, reduced postoperative pain, and earlier discharge.
	recovery	Return to daily activities was observed in minimally invasive cohorts.
Implementation Challenges	Learning curve	Longer operative and cardiopulmonary bypass times were commonly reported during early adoption phases, improving with surgical experience.
	Resources	Minimally invasive and robotic techniques required.
	requirements	specialized equipment and multidisciplinary team expertise.
	Cost	Higher initial procedural costs were reported, particularly for robotic-assisted surgery.
Future Perspectives	Technological	Increasing adoption of robotic-assisted and endoscopic.
	Innovation	techniques with improved visualization and precision.
	Perioperative care	Integration of enhanced recovery after surgery (ERAS) protocols to optimize outcomes.
	Training	Emphasis on structured training programs and simulation-based education to reduce learning curves.

Challenges in the Implementation of Minimally Invasive Cardiac Surgery

Despite the observed clinical benefits, multiple studies highlighted significant challenges associated with the adoption and implementation of MICS. One of the most frequently reported challenges was the learning curve, with several studies documenting longer operative and cardiopulmonary bypass times during the early phases of minimally invasive program development. These differences tended to diminish in high-volume centers and with increased surgeon experience, underscoring the importance of institutional expertise [20].

Additional challenges included the need for specialized surgical teams, advanced anesthetic and perfusion strategies, and the requirement for peripheral cannulation techniques, which may increase procedural complexity. Economic considerations were also reported as a barrier, particularly for robotic-assisted and endoscopic approaches, due to higher capital investment and maintenance costs. Several studies noted variability in patient selection criteria, which contributed to heterogeneity in reported outcomes and limited the generalizability of results across different healthcare settings.

Future Perspectives and Emerging Trends in Minimally Invasive Cardiac Surgery

The included studies identified several emerging trends that reflect the future direction of minimally invasive cardiac surgery. Robotic-assisted and fully endoscopic techniques were increasingly reported and associated with further reductions in postoperative pain, length of hospital stay, and time to return to daily activities compared with conventional minimally invasive approaches. These advancements were facilitated by improvements in imaging technology, instrument design, and perioperative care pathways.

Furthermore, several studies emphasized the growing integration of enhanced recovery protocols, digital planning tools, and simulation-based training to optimize outcomes and shorten learning curves. Although long-term outcome data and cost-effectiveness analyses remain limited, the overall trend suggests a continued expansion of minimally invasive techniques toward more complex cardiac procedures. The results indicate that future research will likely focus on standardizing techniques, refining patient selection, and evaluating long-term clinical and economic outcomes to support broader implementation of MICS.10.

DISCUSSION

This systematic review provides a comprehensive synthesis of contemporary evidence on minimally invasive cardiac surgery (MICS), focusing on clinical outcomes, implementation challenges, and future perspectives. The findings demonstrate that, in appropriately selected patients and experienced centers, MICS offers comparable safety and superior short-term clinical benefits when compared with conventional median sternotomy. These results reinforce the growing body of literature supporting the transition toward less invasive approaches in modern cardiac surgical practice.

Clinical Implications of Improved Short-Term Outcomes

One of the most consistent findings across the included studies was the favorable short-term clinical profile of MICS. Reduced intraoperative blood loss, lower transfusion requirements, and shorter intensive care unit and hospital stays were repeatedly observed across different procedures, including mitral and aortic valve surgery. These outcomes are clinically meaningful, as they are associated with reduced perioperative morbidity, faster functional recovery, and potentially lower healthcare resource utilization. Importantly, the absence of significant differences in perioperative and 30-day mortality between MICS and conventional approaches suggests that reduced invasiveness does not compromise procedural safety when patient selection and surgical expertise are appropriate [1,3].

The reduction in wound-related complications, particularly sternal wound infections, represents another important clinical advantage of MICS. Avoidance of full sternotomy minimizes disruption of bony and soft tissue structures, which is especially beneficial in patients with obesity, diabetes, or advanced age populations known to be at higher risk for sternal complications. These findings support the role of MICS as a patient-centered surgical strategy aimed at improving postoperative quality of care rather than merely reducing incision size.

Learning Curve and Institutional Experience

Despite its advantages, the implementation of MICS is inherently complex and strongly influenced by institutional experience. Several studies included in this review reported longer operative and cardiopulmonary bypass times during early adoption phases, reflecting a steep learning curve. This observation underscores the importance of structured training, mentorship programs, and gradual case selection during the establishment of MICS programs. Notably, high-volume centers demonstrated a marked reduction in operative times over time, with outcomes equal to or exceeding those of conventional surgery, highlighting that technical efficiency improves with experience [10]. The dependence on multidisciplinary collaborationincluding anesthesiology, perfusion, nursing, and intensive care teams, was also emphasized across studies. MICS requires coordinated perioperative planning, alternative cannulation strategies, and advanced intraoperative monitoring. As such, institutional readiness and system-level support are critical determinants of successful implementation. These factors may partially explain the heterogeneity of outcomes reported in lower-volume or resource-limited settings.

Economic Considerations and Resource Allocation

Economic implications represent a major challenge to the widespread adoption of MICS, particularly for robotic-assisted and fully endoscopic techniques. Several studies reported higher upfront procedural costs related to specialized equipment, longer setup times, and maintenance of robotic platforms. However, these costs may be offset by reductions in length of hospital stay, faster return to work, and lower rates of postoperative complications. The variability in cost-effectiveness findings across studies likely reflects differences in healthcare systems, reimbursement models, and institutional efficiency [14].

From a policy perspective, these findings suggest that cost evaluations of MICS should extend beyond procedural expenses and incorporate broader economic outcomes, including indirect costs and patient-reported quality-of-life measures. Future studies employing standardized health economic methodologies are needed to clarify the long-term value proposition of MICS in diverse healthcare settings.

Future Directions and Technological Innovation

The results of this review highlight several emerging trends that are likely to shape the future of minimally invasive cardiac surgery. Robotic-assisted and advanced endoscopic techniques are increasingly being adopted and appear to confer additional benefits in terms of postoperative pain reduction and functional recovery. Moreover, integration of enhanced recovery after surgery (ERAS) protocols, digital surgical planning, and simulation-based training may further optimize outcomes and reduce learning curves [14].

Nevertheless, the expansion of MICS toward more complex procedures must be accompanied by rigorous evaluation of long-term outcomes, durability of repairs, and patient-centered endpoints. Current evidence remains limited with respect to long-term survival, valve durability, and comparative effectiveness across different minimally invasive platforms. Addressing these gaps will be essential to guide evidence-based expansion of MICS indications [17,18].

Strengths and Limitations of the Evidence

The strengths of this systematic review include its focus on contemporary literature, inclusion of multiple study designs, and synthesis of data across a wide range of minimally invasive techniques. However, several limitations should be acknowledged. The predominance of observational studies introduces potential confounding and selection bias,

despite generally consistent findings across studies. Additionally, heterogeneity in surgical techniques, outcome definitions, and follow-up durations limited the feasibility of quantitative meta-analysis for several outcomes [16].

Publication bias and the concentration of studies from high-volume centers may also limit the generalizability of findings to lower-resource settings. These limitations highlight the need for multicenter randomized trials and standardized reporting frameworks to strengthen the evidence base for MICS.

Overall Interpretation

Taken together, the findings of this systematic review suggest that minimally invasive cardiac surgery represents a safe and effective alternative to conventional sternotomy, offering meaningful improvements in short-term clinical outcomes without compromising patient safety. Successful implementation, however, is contingent upon institutional expertise, multidisciplinary collaboration, and careful patient selection. As surgical technology continues to evolve, ongoing evaluation of clinical outcomes, economic impact, and long-term durability will be essential to fully define the role of MICS in contemporary cardiac surgery [17].

CONCLUSION

This systematic review demonstrates that contemporary minimally invasive cardiac surgery (MICS) is a safe and effective alternative to conventional median sternotomy, offering comparable short-term mortality outcomes alongside clear advantages in perioperative morbidity and postoperative recovery. Across a broad range of cardiac procedures, MICS was consistently associated with reduced blood loss, lower transfusion requirements, shorter intensive care unit and hospital stays, and improved early functional recovery. These benefits highlight the clinical value of minimally invasive approaches in enhancing patient- centered outcomes without compromising procedural safety.

However, the successful implementation of MICS is highly dependent on institutional experience, surgeon expertise, and the availability of advanced technology. Challenges related to learning curves, resource allocation, and economic considerations remain significant barriers to widespread adoption, particularly in low- and medium-volume centers. Overall, the findings of this review support the integration of MICS into contemporary cardiac surgical practice, while emphasizing the need for structured training programs, standardized patient selection criteria, and ongoing evaluation of long-term outcomes.

ETHICAL CONSIDERATIONS

This systematic review was conducted in accordance with established ethical standards for secondary research. As the study involved only the analysis and synthesis of data from previously published literature, ethical approval and informed consent were not required. No individual patient data were accessed or analyzed, and all included studies were assumed to have obtained appropriate ethical approval as reported by the original authors. The review adhered to the PRISMA 2020 guidelines and principles of transparency, scientific integrity, and responsible reporting, with all sources appropriately cited to acknowledge original contributions and avoid plagiarism.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this article.

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