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Beyond Technical Innovation: Organizational and Economic Evaluation of Minimally Invasive Cardiac Surgery – a Narrative Review and Hospital-Level Framework

Yerzhan Saparbay[1], Yerlan Orazymbetov[1,2], Argul Razbekova[3], Serik Aitaliyev[2], Margulan Uazhanov[4]

[1]*Department of Cardiac Surgery, JSC National Scientific Medical Research Centre, Astana, Kazakhstan*
[2]*Department of Cardiac, Thoracic and Vascular Surgery, Hospital of Lithuanian University of Health Sciences Kauno Klinikos, Lithuanian University of Health Sciences, Kaunas, Lithuania*
[3]*Administrative and Management Division, City Cardiology Centre, Almaty, Kazakhstan*
[4]*Department of Public Health and Management, Astana Medical University, Astana, Kazakhstan*

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Corresponding author:
Yerlan Orazymbetov
E-mail: doctoryerlan@gmail.com.
ORCID: 0009-0008-0844-7268.

ABSTRACT

Background: Minimally invasive cardiac surgery (MICS) is increasingly recognized as an integrated perioperative care model rather than simply a small-incision surgical technique. Its clinical and economic value depends on patient selection, team experience, recovery pathways, institutional resources, and local cost structures.

Objective: This narrative review summarizes the current evidence on the clinical, organizational, and economic value of MICS, and proposes a practical hospital-level framework for evaluating program performance and maturity.

Methods: A structured narrative search of PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar was conducted between January 2010 and June 2026. The review focused on minimally invasive valve surgery, coronary revascularization, enhanced recovery pathways, programme learning curves, resource utilization, and hospital cost analyses. The conduct and reporting of the review were guided by the Scale for the Assessment of Narrative Review Articles (SANRA). Evidence was synthesized across four domains: clinical safety and effectiveness, programme maturity and learning curves, organizational performance, and economic performance. Since the review was interpretive rather than systematic, a formal duplicate-screening workflow, PRISMA flow diagram, or study-level risk-of-bias instrument was not utilized.

Results: MICS can provide outcomes comparable to conventional sternotomy, with shorter intensive care and hospital stays, lower transfusion requirements, fewer wound complications, and earlier mobilization. However, higher operative costs, specialized equipment, longer cardiopulmonary bypass and cross-clamp times, peripheral cannulation risks, conversion to sternotomy, and learning-curve effects may offset postoperative savings. Economic value therefore depends on whether reduced surgical trauma translates into fewer complications and lower overall resource use.

Conclusion: MICS should be evaluated as a value-based care model. Centres developing MICS programmes should monitor risk-adjusted outcomes, resource utilization, conversions, total costs and learning curve dynamics through a structured institutional registry.

Keywords: minimally invasive cardiac surgery; health economics; resource utilization; recovery; learning-curve; value-based healthcare.

Introduction

Cardiac surgery remains one of the most technically demanding and resource-intensive areas of hospital care [1]. For decades, median sternotomy has been the standard access for most cardiac surgical procedures due its wide exposure and rapid control [2,3]. However, full sternotomy is associated with significant surgical trauma, postoperative pain, wound complications, increased transfusion requirements and delayed recovery [4]. These limitations have led to the development of less invasive surgical strategies [5–8].

Minimally invasive cardiac surgery (MICS) encompasses a spectrum of techniques, ranging from mini-sternotomies and mini-thoracotomies to video-assisted, totally endoscopic, and robotic-assisted approaches, which are now routinely used in valve surgery, coronary revascularisation, and selected combined procedures [2,4,9,10]. Over time, MICS has transformed from a simple incision strategy into a comprehensive perioperative care model that requires highly coordinated workflows across the surgical, anaesthetic, perfusion, intensive care, and nursing domains [6,7,11].

While the potential advantages of MICS include reduced trauma, fewer transfusions, and faster recovery, these benefits are neither universal nor guaranteed [12,13]. MICS frequently prolongs cardiopulmonary bypass and cross-clamp times, requires specialised equipment, and demands a substantial institutional learning curve [14,15]. Consequently, a central challenge in evaluating MICS is the financial and operational misalignment across the hospital episode: the intraoperative period is often significantly more expensive due to prolonged operating time and specialised disposables, whereas the postoperative period generates savings through reduced intensive care unit (ICU) and hospital stays [16–19]. This tension is particularly acute for resource-constrained healthcare systems and tertiary centres, where ICU capacity is a major operational bottleneck and investments in technology must be justified by measurable hospital-wide utility. Institutional value also depends on programme maturity; early implementation typically incurs high costs and longer procedures, whereas experienced teams achieve predictable recovery pathways and efficient resource utilisation [3,11].

Although recent state-of-the-art reviews have extensively examined the historical and technical evolution of MICS [4,10], less attention has been paid to how hospitals can determine whether a programme generates measurable institutional value [20]. Current literature often reports clinical outcomes, recovery, costs, or learning curves in isolation. An integrated framework is needed to connect these aspects while maintaining procedure-specific benchmarks.

The aim of this narrative review is to analyze the current evidence regarding to the organizational and economic value of MICS. Additionally, the review proposes a practical framework for evaluating MICS programs at tertiary cardiac centres. The novel aspect of this review is the integration of risk-adjusted clinical outcomes, organizational performance, total episode costs, and program maturity into a unified governance framework. This framework is designed for local implementation and does not suggest that different MICS procedures are clinically interchangeable.

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Methods

Review design

This article is presented as a narrative review and practical framework paper. Its aim is not to perform a formal meta-analysis or to assert that MICS is superior to conventional surgery. Instead, it identifies the clinical, organizational, economic, and programme conditions under which MICS may generate value. The review was conducted according to the principles of transparent narrative synthesis and followed the Scale for the Assessment of Narrative Review Articles (SANRA) [21]. Due to significant differences in study procedures, patient populations, comparators, institutional experiences, healthcare systems, economic methodologies, and outcome definitions, quantitative pooling of the data was not appropriate. As a result, the evidence was organized into clinically relevant domains and translated into a practical evaluation model for hospital governance.

Search strategy and study selection

PubMed/MEDLINE, Scopus, Web of Science and Google Scholar were searched for English-language publications published from January 2010 to June 2026, with the final search conducted in June 2026. The search terms included combinations of “minimally invasive cardiac surgery,” “minimally invasive mitral valve surgery,” “minimally invasive aortic valve replacement,” “robotic cardiac surgery,” “robotic coronary artery bypass grafting,” “minimally invasive coronary revascularization,” “enhanced recovery after cardiac surgery,” “early discharge,” “intensive care unit,” “length of stay,” “transfusion,” “cost analysis,” “cost-effectiveness,” “learning curve,” “conversion,” “peripheral cannulation,” “value-based healthcare” and “middle-income countries.” Additionally, the reference lists of major reviews and relevant primary studies were examined.

Eligible types of evidence included randomized trials, prospective and retrospective cohort studies, propensity-matched studies, registry analyses, systematic reviews, meta-analyses, and hospital-based economic evaluations. Narrative reviews were used to provide technical context, describe programme implementation, and highlight additional primary studies. Trial protocols were considered only as contextual information and were not regarded as evidence of clinical or economic outcomes. Studies focused exclusively on paediatric populations, conference abstracts without full text, isolated technical descriptions without outcome data, non-peer-reviewed materials, and publications unrelated to hospital-level value evaluation were excluded. In line with the narrative design, a formal duplicate-screening process, study-count flow diagram, or study-level risk-of-bias scoring was not performed.

Evidence synthesis

Evidence was organized into four predefined domains: (1) clinical safety and effectiveness; (2) organizational performance and recovery; (3) economic performance; and (4) program maturity. The review prioritized several key metrics, including mortality rates, stroke incidence, myocardial infarction, bleeding events, reoperations, acute kidney injury, pacemaker implantation, and wound and vascular complications. It also assessed conversion rates, ventilation time, stays in the ICU and wards, total length of stay, discharge destination, readmission rates, transfusions, operative and postoperative costs, total episode costs, annual patient volume, chronological case numbers, and learning curve dynamics. Each evidence stream was analyzed based on procedure type, access route, comparator, and program maturity, rather than being consolidated into a single effectiveness estimate. The framework is procedure-agnostic at the governance level, but benchmarking must remain specific to each procedure. Programs for mitral, aortic, coronary, mini-sternotomy, mini-thoracotomy, and robotic surgeries should be stratified and not combined, unless there is a clearly defined analytical rationale for doing so.

Development of the hospital-level framework

The proposed framework was developed by mapping recurring variables from the clinical, organizational, economic, and implementation literature to four predefined domains. Candidate indicators were selected based on three practical criteria: clinical relevance, feasibility of measurement using routinely collected hospital data, and usefulness for ongoing program governance. The synthesis process was iterative and pragmatic rather than conducted through a formal Delphi or consensus process. Accordingly, the framework is intended as an adaptable institutional measurement tool rather than a validated universal cost-effectiveness model, because reimbursement systems, staffing costs, device prices, accounting standards, and discharge infrastructure vary across healthcare systems. The governance framework itself is procedure-agnostic; however, clinical benchmarking and economic comparisons must remain procedure-specific. Analyses should therefore be stratified by procedure type (mitral valve surgery, aortic valve surgery, or coronary revascularisation) and by access strategy or technology (mini-sternotomy, mini-thoracotomy, or robotic assistance), unless a prespecified methodological rationale supports pooling.

MICS as an Integrated Care Model

A narrow definition of minimally invasive cardiac surgery (MICS) that focuses only on the length or location of the incision is inadequate. Although reduced access trauma allows quicker recovery, how effectively this opportunity is realized depends on the surrounding perioperative system. Key factors include patient selection, preoperative monitoring, cannulation planning, anaesthesia, perfusion, myocardial protection, pain management, early extubation, timely removal of drains and catheters, mobilization, discharge criteria, and post-discharge follow-up [6–8,13,22,23].

Even if a mini-thoracotomy is technically successful, prolonged hospitalization can occur if pain management is insufficient, extubation is delayed, mobilization is inconsistent, or discharge criteria are unclear. On the other hand, patients who undergo sternotomy within a well-established enhanced recovery pathway may experience rapid recovery [7]. The impact of MICS should therefore be viewed as an interaction between surgical access and pathway performance, rather than as an inherent advantage of having a smaller incision [24].

This distinction has important practical implications. A program that introduces a new access route without standardized patient selection, team training, enhanced recovery protocols, clear outcome definitions, cost tracking, and monitoring of the learning curve may complicate the procedure without demonstrating benefits.

Safety, Outcomes and Patient Selection

The contemporary evidence generally supports the feasibility and safety of MICS for appropriately selected patients treated by experienced teams. The UK Mini Mitral randomized trial demonstrated that minithoracotomy achieved high-quality, durable mitral repair with safety outcomes similar to those of sternotomy. However, it was not superior for the primary physical-function endpoint at 12 weeks [25].

Meta-analyses of mitral surgery suggest broadly comparable mortality and major morbidity rates between the two approaches, with potential benefits in terms of hospital stay and recovery outcomes [26]. For aortic valve replacement, both meta-analytic and Cochrane evidence suggest that limited-access techniques can reduce ICU or total hospital stay in some cases; however, these approaches may lead to longer bypass and cross-clamp times, and the reliability of outcomes varies [12,14].

The strongest value proposition is unlikely to be a universal reduction in mortality rates, as mortality in elective cardiac surgery is already low and heavily influenced by baseline risk factors. More plausible benefits of improved surgical techniques and care include reduced exposure to blood transfusions, fewer sternal wound- related complications, shorter ventilation and

ICU stays, earlier mobilization of patients, and faster overall functional recovery. Although these outcomes are clinically significant, their impact can vary depending on the specific procedure, the patient's profile, the maturity of the surgical program, and the perioperative pathway used [14,23,26].

MICS also has an access-specific risk profile. Peripheral cannulation may be associated with vascular injury, bleeding, groin infection, lymphatic complications, limb ischemia, and concerns related to retrograde perfusion in patients with aortic atherosclerosis. Limited exposure may require conversion to sternotomy because of bleeding, adhesions, haemodynamic instability, difficult anatomy, inadequate visualization, or an inability to achieve a safe, durable repair or revascularization. Conversion should be recorded prospectively as a safety and programme-maturity endpoint rather than concealed as an isolated technical failure [9,13,15].

Patient selection is therefore central to both clinical outcomes and economic interpretation. Mitral surgery requires assessment of pathology, repair complexity, annular or leaflet calcification, ventricular function, pulmonary hypertension, prior surgery, chest anatomy, vascular access, and the anticipated probability of a durable repair [9]. Aortic valve strategy depends on valve morphology, aortic anatomy, vascular access, frailty, comorbidities, and the relative suitability of surgical and transcatheter options. Minimally invasive coronary revascularization requires evaluation of target vessel anatomy, conduit strategy, completeness of revascularization, peripheral vascular status, and the feasibility of hybrid treatment [4,5].

Because MICS cohorts are frequently selected for anatomical suitability and lower procedural complexity, unadjusted comparisons may overestimate benefit. Hospital evaluations should use risk adjustment, propensity methods, stratification, or multivariable modelling when comparing MICS with sternotomy. Comparative analyses should remain specific to each procedure and should not combine mitral, aortic, coronary, mini-sternotomy, mini-thoracotomy, and robotic procedures without a predefined rationale. The heart team should also be treated as an auditable organizational process: the programme should document whether the case was discussed, which options were considered, why MICS was selected or rejected, and whether the decision conformed to predefined criteria.

Organizational Performance: Enhanced Recovery, Pain, and Discharge

Enhanced recovery is one of the main mechanisms through which MICS can generate organizational value. Cardiac ERAS recommendations emphasize preoperative education and optimization, anaemia management, multimodal analgesia, early extubation, prevention of delirium and nausea, blood conservation, early mobilization, and standardized discharge planning [22]. MICS-specific reviews and cohort studies indicate that these elements are most effective when implemented as a coordinated pathway rather than as isolated interventions [7,23].

Pain management requires particular attention. Thoracic access may still produce substantial pain through intercostal nerve irritation, pleural manipulation, retraction, and chest drains. Poor analgesia impairs respiratory exercises, mobilization, physiotherapy, sleep, and readiness for discharge. Multimodal systemic analgesia and selected regional techniques can reduce opioid exposure and support recovery, although protocols vary and evidence is heterogeneous[6,13]. Pain should therefore be measured as a pathway performance variable rather than treated solely as a comfort outcome.

Early discharge is meaningful only when it reflects clinical readiness. In selected, uncomplicated patients after minimally invasive valve surgery, discharge within three postoperative days has been associated with comparable short-term outcomes and lower costs, but strong selection effects must be recognized [8]. Hospitals should define minimum discharge criteria that include stable rhythm and haemodynamics, no oxygen dependency, adequate pain control and mobility, acceptable renal function, no major wound or groin problem, no clinically important pleural or pericardial collection, an appropriate anticoagulation plan, and clear access to follow-up.

Organizational performance should be measured using hours as well as calendar days. Ventilation duration, time to mobilization, ICU hours, time to drain removal, ward days, discharge destination, and 30-day readmission together provide a more informative picture than hospital length of stay alone. A short admission achieved through premature discharge is not a benefit if it increases emergency visits or readmissions. Conversely, reduced ICU use may improve bed availability, reduce cancellations, and increase surgical throughput even when direct accounting savings are modest.

Technical Complexity, Learning Curve, and Programme Maturity

MICS is a team-dependent technical platform. It may require peripheral cannulation, long-shafted instruments, thoracoscopic or robotic visualization, advanced transesophageal echocardiography, alternative myocardial protection strategies, and close coordination among surgeons, anaesthesiologists, perfusionists, nursing staff, imaging specialists, and the ICU team [11,13,15]. During early implementation, operative duration, bypass and cross-clamp times, conversion rates, and resource use may be higher than during the mature phase.

The learning curve should be measured rather than assumed. A recent systematic review and meta-analysis of MICS procedures revealed significant variation in the number of cases needed to achieve consistent performance [16]. This variation reflects procedure complexity, prior surgeon experience, case selection, proctoring, team consistency, and institutional volume. The relevant unit of learning is therefore not only the individual surgeon but the multidisciplinary programme.

Programme maturity should therefore be assessed longitudinally, using chronological case number, annual procedural volume, operative and bypass times, conversion, transfusion, complications, ICU use, hospital stay, readmission, and cost. Moving averages, phase-based comparisons, and cumulative-sum methods can identify improvement, deterioration, or persistent process failures. Early-implementation and mature-programme results should be reported separately; a single average across all cases may obscure both learning-related risk and later efficiency gains.

Low annual volume creates a distinct challenge: a team may complete the initial learning phase yet fail to maintain proficiency. Centres should define a realistic procedural scope, select early cases conservatively, use proctoring and simulation where available, standardize equipment and team composition, and review adverse events through multidisciplinary audit. Expansion of indications should follow demonstrated stability in safety and process metrics rather than technical enthusiasm alone.

Economic Evaluation: Total Episode Cost and Complication Burden

Economic studies of MICS report heterogeneous findings, which is expected because costs depend on procedure type, device prices, operative duration, accounting methods, staffing, reimbursement, ICU practice, discharge culture, complication rates, and programme maturity [17–20]. Results from one health system cannot be transferred directly to another without adjustment for local unit costs and care pathways.

A hospital-level analysis should separate at least three cost layers. The first is procedural cost, including operating-room time, anaesthesia, perfusion, imaging, instruments, disposables, prostheses or rings, robotic acquisition or depreciation, maintenance, sterilization, and training. The second is routine postoperative cost, covering ICU and ward care, medications, laboratory testing, imaging, physiotherapy, and transfusion. The third is complication-related cost, which includes conversion, reoperation for bleeding, stroke, renal replacement therapy, pacemaker implantation, infection, sepsis, prolonged ventilation, readmission, and reintervention.

Available studies illustrate why operative cost alone can be misleading. In minimally invasive mitral surgery, higher procedural expenditure may be offset by lower transfusion use, shorter ICU or ward stay, and reduced downstream resource consumption [19,20]. Economic analyses of minimally invasive aortic valve replacement and robot-assisted coronary surgery likewise show that the balance between higher technology or operating room costs and postoperative savings is highly context dependent [17,18]. The most informative internal endpoint is therefore total hospital episode cost, ideally from admission through discharge, plus 30-day readmission and early complication costs.

Complications should be analyzed simultaneously as clinical and economic events. A rare stroke, reoperation, vascular complication, or prolonged ventilation episode may outweigh savings from many uncomplicated short stays. Programmes should report both complication frequency and cost. When detailed micro-costing is unavailable, a pragmatic model can use local average costs for the operation, ICU days, transfusion, reoperation, major complications, and readmission.

The term "cost-effectiveness" should be reserved for analyses with an explicit effectiveness denominator, such as quality-adjusted life years, validated measures of functional recovery, or other defined patient outcomes. For routine governance, "cost analysis", "resource utilization analysis", and "total episode cost" are usually more accurate. Within a value-based healthcare perspective, value reflects outcomes achieved relative to total cost, not cost reduction alone [27,28].

Proposed Hospital-Level Evaluation Framework

The proposed framework is intended for tertiary cardiac centres introducing, evaluating, or scaling a MICS programme. It links four domains, including clinical outcomes, organizational performance, economic performance, and programme maturity, where distinguishes a mandatory core dataset from optional research-grade variables. The primary dataset should be collected prospectively using predefined, procedure-specific definitions that align, where possible, with recognized national registries and consensus endpoint standards. This framework serves as a governance tool for local measurement and comparison, rather than functioning as a universal cost-effectiveness model.

Table 1 Evidence domains and their implications for hospital-level MICS evaluation

Domain	Representative evidence	Main signal	Implication for hospitals
Clinical safety and effectiveness	Randomized, matched, registry, and meta-analytic evidence [5, 9, 12, 14, 25, 26, 29, 30]	Comparable safety in selected patients; effects vary by procedure and programme maturity	Use risk-adjusted, procedure-specific benchmarks; stratify distinct procedures; record conversion and access-related complications
Organizational performance	ERAS, pain, and early-discharge studies [6–8, 13, 22, 23]	Shorter ICU or hospital stay is pathway-dependent	Measure ventilation, ICU hours, mobilization, discharge readiness, destination, and readmission
Economic performance	Hospital cost analyses [17–20]	Postoperative savings may offset higher procedural cost	Analyze local cost layers and total episode cost rather than operating-room cost alone
Programme maturity	Learning-curve and programme reports [10, 11, 15, 16]	Efficiency, conversion and resource use change with cumulative experience	Track chronological case number, annual volume, temporal trends, mentoring, and audit

The principal evidence domains, their main signals, and their implications for hospital-level MICS evaluation are summarized in Table 1.

The core framework should address five key questions:

1. Were patients appropriately selected?
2. Was the procedure conducted safely?
3. Did recovery and resource utilization improve?
4. Did the total cost of the episode change?
5. Did performance improve with experience?

These questions should be examined collectively and within procedure-specific strata. A shorter length of stay without ensuring adequate safety, or low operative costs accompanied by a high complication rate, do not truly represent value. The minimum indicators required to answer these questions are outlined in Table 2 (see the next page).

The core dataset must remain appropriate for routine clinical use. Centers that have adequate research, informatics, and analytical resources may choose to collect additional variables to study aspects such as functional recovery, components of care pathways, capacity effects, detailed cost analysis, and program evaluation. These extended research-grade and service-development variables are presented in Table 3 (see the next page).

Implementation cycle

To operationalize the proposed framework, institutions should follow a continuous, five-step implementation cycle (see Figure 1). This structured workflow bridges clinical decision-making with continuous quality improvement:

1. Define the specific eligibility criteria and contraindications for the procedure, and document the decisions made by the heart team.

2. Standardize the perioperative pathway, which includes monitoring, anesthesia, perfusion, analgesia, extubation, drain removal, mobilization, and discharge criteria.

3. Collect the core dataset prospectively, using predefined definitions for outcomes and conversions (see Table 2).

4. Calculate the resource utilization and total episode cost,

Table 2 Core dataset for hospital-level value evaluation of MICS

Domain	Core indicators	Timing	Purpose
Case mix and risk	Age, sex, BMI, diabetes, COPD, renal disease, previous cardiac surgery; EuroSCORE II or STS risk; LVEF; NYHA class	Baseline and admission	Risk adjustment and case-mix comparison
Anatomy and selection	Valve or coronary pathology, calcification, chest anatomy, vascular access, heart-team decision and reason for approach	Preoperative	Selection transparency and access planning
Procedure	Operation and access type, cannulation strategy, the time of surgery, CPB and cross-clamp	Intraoperative	Technical complexity and resource use
Safety	Conversion (definition and reason), operative mortality, stroke/TIA, myocardial infarction, reoperation for bleeding, AKI/dialysis, pacemaker implantation, vascular complications, and wound complications	In hospital and 30 days	Risk-adjusted safety and complication-cost analysis
Recovery	Ventilation hours, mobilization, pain control, ICU hours, total hospital stay	Postoperative	Organizational performance
Discharge	Discharge readiness, destination, postoperative day of discharge, emergency visits, 30-day readmission, and cause	Discharge and 30 days	Safety of accelerated pathways
Blood management	PRBC, FFP, platelet, and fibrinogen-product exposure	In hospital	Clinical outcome and cost driver
Economics	Procedural, ICU, ward, transfusion, complication, and total episode costs	Admission to 30 days	Hospital-level economic performance
Programme maturity	Chronological case number, annual volume, surgeon/team experience, conversion and key outcomes over time	Continuous	Learning curve and scaling decisions

Definitions note: Each program should specify outcome and conversion definitions in advance, aligning them where applicable with recognized procedure-specific standards. Definitions based on STS can support outcomes in adult cardiac surgery, MVARC can aid in mitral valve endpoints, and VARC-3 can assist with aortic valve endpoints [31–33].

including major complications and 30-day readmissions where applicable.

5. Analyze performance based on the chronological case number and the phase of the program. Review the results through a multidisciplinary audit and use predefined thresholds to guide decisions regarding expansion or corrective actions (see Table 3).

Application in Tertiary and Resource-Constrained Settings

The transferability of published economic results is limited in settings where staff costs, ICU-day costs, reimbursement rates, device pricing, discharge infrastructure, and rehabilitation pathways differ from those in the original studies. For such centers, the primary focus should not be on a complex cost-utility model, but rather on establishing a reliable institutional registry linked to practical local costing. The core indicators presented in Table 2 provide a feasible starting point for such a registry.

A relatively small core dataset can address management questions that are directly relevant to program governance. For instance, are MICS and sternotomy patients comparable in terms

Table 3 Extended variables for research-grade and service-development analysis

Area	Extended variables	Analytical value
Frailty and function	Frailty scale, baseline mobility, 6-minute walk distance, return to activity, quality of life	Tests whether benefit is expressed through functional recovery rather than mortality
Pain and analgesia	Serial pain scores, opioid consumption, regional block, nausea, sleep	Links pathway components to mobilization and discharge
Detailed blood management	Cell salvage, coagulation testing, individual blood components	Identifies modifiable transfusion drivers
Imaging and access planning	Computed tomography vascular assessment, echocardiographic anatomy, calcification categories	Supports prediction of conversion and access complications
Readmission detail	Timing, cause, intervention, and cost	Tests whether accelerated discharge shifts cost beyond the index admission
Capacity effect	ICU bed turnover, cancelled operations, waiting-list metrics, throughput	Captures organizational value not visible in direct cost accounting
Cost granularity	Personnel time, disposables, robotic depreciation and maintenance, diagnostics	Identifies modifiable local cost drivers
Learning-curve analysis	CUSUM, moving averages, phase-based analysis, surgeon and team exposure	Distinguishes early implementation from mature performance

of baseline risk? Does MICS lead to reduced ICU hours, shorter total hospital stays, fewer transfusions, or lower rates of wound complications locally? Does it increase operative time or the need for conversions? Which complications incur the greatest costs? Do total episode costs decrease, increase, or remain similar? Does performance improve as experience accumulates?

Capacity effects are particularly significant when ICU beds are limited. A shorter ICU stay may improve access for other patients, reduce the cancellation of planned operations, and enhance overall throughput. These benefits should be reported separately from direct financial savings, as they represent opportunity value rather than necessarily indicating a reduction in pre-booked expenditures. Suggested indicators for measuring these capacity effects are included in Table 3.

For academic tertiary centers, the registry also serves as a platform for quality improvement and research. The same structured data can support service evaluations, doctoral projects, comparative-effectiveness studies, economic analyses, and publications. Therefore, data collection should ideally be designed collaboratively by clinicians, hospital administration, information technology staff, and health economists. Depending on institutional resources and research objectives, the core dataset in Table 2 may be supplemented with additional variables listed in Table 3.

Discussion

The available evidence indicates that minimally invasive cardiac surgery (MICS) is not inherently superior or cost-saving. However, in carefully selected patients and at experienced facilities, minimally invasive techniques can achieve a level of clinical safety comparable to traditional sternotomy while enhancing certain recovery and resource-use outcomes [12,14,25,26,29,30]. However, these benefits are not produced

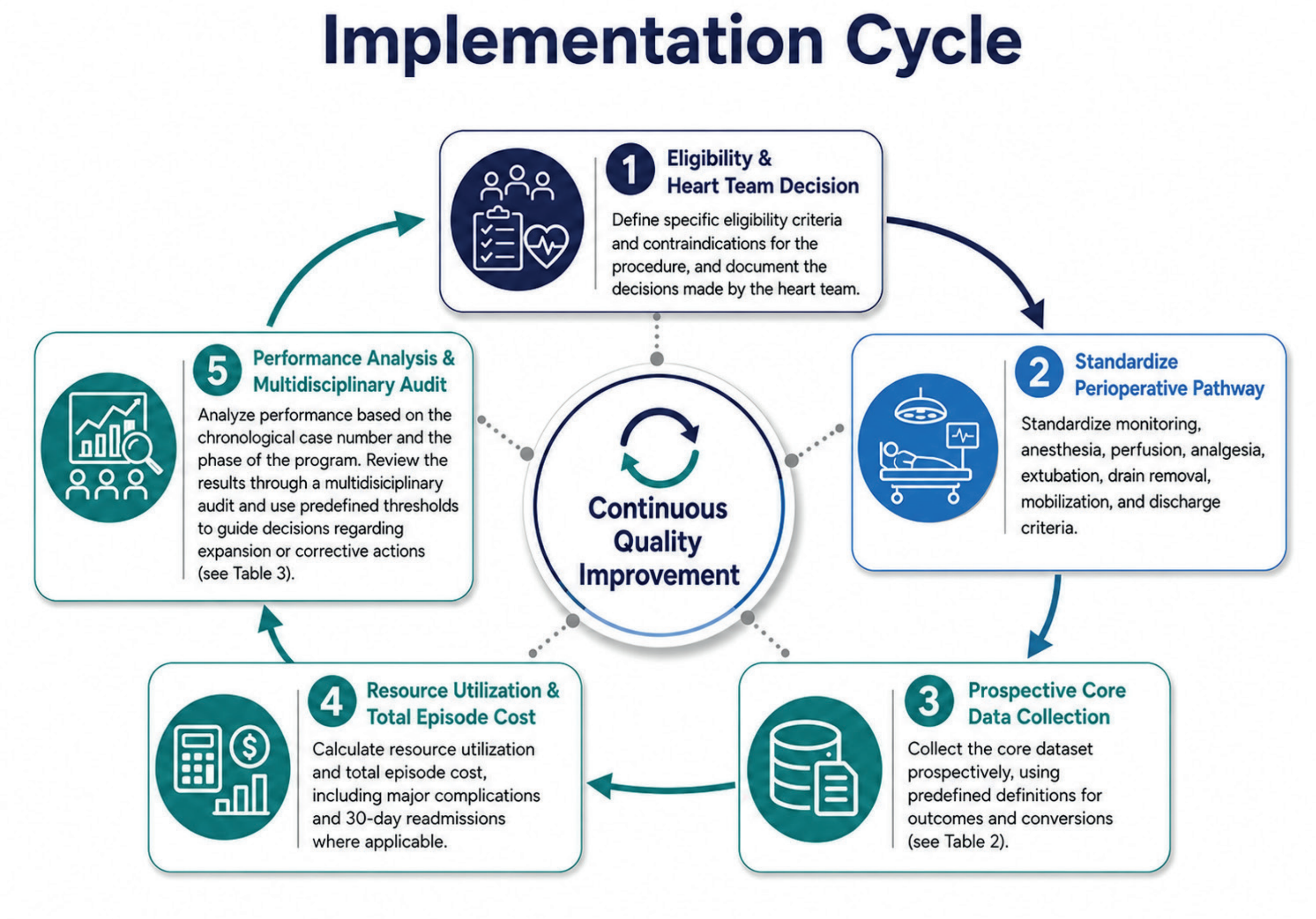

Figure 1 – MICS program implementation and governance cycle

A continuous five-step framework integrating Heart Team–based patient selection, perioperative pathway standardization, prospective data collection, local resource utilization and cost evaluation, and longitudinal learning-curve analysis using CUSUM.

by the incision alone. They arise when reduced surgical trauma is translated into measurable improvements through the entire perioperative care pathway.

This distinction helps explain the heterogeneity of published findings. Established programmes with disciplined patient selection, experienced and stable multidisciplinary teams, standardized anaesthetic and perfusion protocols, effective pain control, early extubation, structured mobilization, and explicit discharge criteria are more likely to convert reduced access trauma into shorter ICU and hospital stays. By contrast, programmes in an early implementation phase may experience longer operating times, higher procedural and device costs, greater variability in postoperative recovery, and additional costs associated with conversion or access-related complications. Combining outcomes from centres at different stages of programme maturity may therefore obscure the conditions under which MICS generates value.

The strongest clinical argument for MICS is not a universal mortality advantage. Mortality after elective cardiac surgery is relatively uncommon and is strongly influenced by baseline risk, procedure type, and case selection. The more plausible benefit is a reduction in the burden of recovery, including shorter ventilation and ICU exposure, lower transfusion requirements, fewer access- or wound-related complications, earlier mobilization, shorter hospitalization, and faster functional recovery. These outcomes are relevant not only to patients but also to hospital operations because they influence ICU capacity, bed turnover, rehabilitation requirements, discharge planning, and readmission.

The economic case must therefore be evaluated across the complete episode of care. If procedural costs increase while the postoperative pathway remains unchanged, the economic advantage of MICS may be limited. Similarly, inappropriate case selection, prolonged operative or cardiopulmonary bypass times, vascular-access complications, frequent conversion, or failure to achieve earlier recovery may weaken the value proposition. Conversely, higher initial operating-room expenditure may be partly or fully offset by reductions in ICU use, ward stay, transfusion, complications, and readmission. The relevant question is therefore not simply whether MICS is less expensive than sternotomy, but under which clinical, organisational, and programme conditions it improves outcomes relative to total hospital resource use.

Risk adjustment is essential when evaluating these outcomes. Observational comparisons are particularly vulnerable to selection bias because patients who are clinically stable and anatomically suitable patients are more likely to undergo minimally invasive procedures. Hospitals should therefore report baseline risk, anatomical eligibility, procedure type, access route, and the rationale for treatment selection. Depending on sample size and data quality, comparative analyses should use multivariable adjustment, propensity-score methods, matching, weighting, or stratification. Unadjusted comparisons should be interpreted as descriptive rather than causal and distinct procedure classes should be analysed separately.

Programme maturity and the learning curve are additional determinants of clinical and economic performance. Early cases should not be excluded from programme evaluation, but they should be analysed separately as an implementation phase. Chronological monitoring of conversion, operative time, cardiopulmonary bypass and cross-clamp duration, complications, ICU utilisation, length of stay, and total episode cost can demonstrate whether initial investment is followed by stabilisation and improved efficiency. Failure to observe improvement should prompt review of patient selection, training, proctoring, team composition, equipment, and perioperative workflow before further programme expansion. Conversely, favourable mature-programme outcomes should not be assumed to apply immediately to centres at the beginning of implementation.

The proposed framework adopts a value-based perspective by linking patient outcomes to the total resources used across the episode of care [28]. The main contribution of this model is to combine four key dimensions into a single governance framework: risk-adjusted safety and effectiveness, organizational performance, total episode cost, and program maturity. This integration is practical, though not formally validated. Hospitals vary in factors such as reimbursement rates, staffing expenses, ICU capacity, device costs, discharge processes, and rehabilitation pathways. As a result, the economic value of minimally invasive cardiac surgery (MICS) needs to be demonstrated locally and for each specific procedure class. While technology facilitates minimally invasive surgery, achieving sustainable value relies on careful patient selection, standardized pathways, multidisciplinary coordination, transparent measurement, and ongoing program governance.

Practical Recommendations

A strong program evaluation must address situations where MICS may not provide value. Key areas for improvement include:

- Avoid expanding procedures before demonstrating stable safety and performance metrics;
- Ensure thorough vascular and anatomical screening prior to peripheral cannulation or limited-access surgery;
- Standardize definitions and reporting of conversions to sternotomy;
- Prevent unnecessary prolongation of bypass or cross-clamp time without clear recovery benefits;
- Improve pain management, patient mobilization, and standardized criteria for enhanced recovery and discharge;
- Treat early discharge as a clinical safety decision rather than an administrative target;
- Fully account for costs related to robotic systems, including acquisition, maintenance, and training;
- Maintain high team proficiency by avoiding low annual procedure volumes and excessive variation in team composition;
- Adjust comparisons with sternotomy for risk factors, anatomy, and treatment-selection bias.

Recognizing these failure points reinforces the value of MICS and emphasizes the necessary safeguards for effective implementation and quality improvement.

Limitations

This review has several limitations.

First, it is a narrative review rather than a systematic one; consequently, it does not include a PRISMA flow diagram, formal duplicate screening, a quantitative study-selection count, study-level risk-of-bias assessment, or a meta-analysis. The structured search was designed to support transparent interpretive synthesis rather than exhaustive effect estimation, which means that study selection is partly dependent on the authors' judgment.

Second, the evidence varies across different procedures, access routes, comparators, patient risk levels, institutional experience, outcome definitions, and economic methods.

Third, many studies are retrospective and conducted at single centers, which increases the potential for selection bias and limits causal inference.

Fourth, cost data are significantly influenced by local reimbursement policies, staffing levels, device pricing, accounting practices, and length-of-stay policies. Therefore, absolute cost estimates should not be directly transferred between countries. Fifth, the maturity of programs and the experience of operators limit the generalizability of findings from high-volume expert centers to new or low-volume programs.

Finally, the proposed framework has not undergone prospective validation, external benchmarking, Delphi consensus, or formal health-economic validation. It should be viewed as a structured starting point for local measurement and governance rather than a replacement for procedure-specific clinical judgment, validated registry definitions, or formal economic evaluations.

Conclusion

Minimally invasive cardiac surgery represents an important evolution in cardiovascular care, but its value should not be judged by incision size alone. MICS creates value only when appropriate patient selection, technical expertise, multidisciplinary planning, anaesthesia and perfusion protocols, effective pain control, enhanced recovery, early mobilization, safe discharge, complication prevention, and outcome monitoring operate as an integrated system.

In selected patients treated within experienced programmes, MICS can achieve outcomes comparable to conventional approaches and may reduce transfusion exposure, wound complications, ICU use, hospital stay, and time to recovery. Economic benefit is most likely when higher procedural expenditure is offset by lower postoperative resource utilization and fewer high-cost complications.

Tertiary cardiac centres should therefore evaluate MICS through a structured institutional registry that combines risk-adjusted clinical outcomes, organizational performance, total episode costs, readmissions, and learning-curve indicators. Such measurement can support clinical governance, responsible programme expansion, resource optimization, and scientific evaluation. MICS should ultimately be understood not only as a surgical technique, but as a patient-centred, value-oriented, and organization-dependent model of cardiac surgical care.

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