Review Article

Minimally Invasive Cardiac Surgery: A Practical Overview for Clinicians

Permyos Ruengsakulrach[1] ; Paradorn Jetwanna[1] ; Nuttapon Arayawudhikul[1]



Permyos Ruengsakulrach

[1] Cardiovascular and Thoracic Surgeon, Bangkok Heart Hospital, Bangkok, Thailand

*Address Correspondence to author:
Permyos Ruengsakulrach,
MD, PhD, FRCST, FCCP, AFEEAT
Cardiovascular and Thoracic Surgeon
Bangkok Heart Hospital
2 Soi Soonvijai 7, New Petchburi Road, Huaykwang,
Bangkok, 10310, Thailand
email: permyos.ru@bangkokhospital.com

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Abstract

Minimally invasive cardiac surgery (MICS) has become an integral component of contemporary cardiovascular care, offering effective surgical treatment while reducing the physical and physiological burden associated with conventional median sternotomy. Through the use of smaller incisions, endoscopic visualization, and refined perioperative management, a broad spectrum of cardiac procedures can now be performed with safety and durability comparable to conventional approaches. These include coronary artery bypass grafting (CABG), mitral and aortic valve surgery, selected congenital heart defect repairs, and other intracardiac interventions.

This review provides a practical overview of minimally invasive cardiac surgery for clinicians involved in the diagnosis, referral, and longitudinal management of patients with heart disease. Key topics include the range of procedures amenable to minimally invasive approaches, fundamental principles underlying their performance, and critical considerations for patient selection. The clinical benefits of MICS—such as reduced postoperative pain, faster recovery, shorter hospital stay, and improved quality of life—are discussed alongside important risks and limitations that may influence procedural choice.

By emphasizing clinically relevant concepts rather than technical operative detail, this article aims to facilitate informed referral, shared decision-making, and effective multidisciplinary collaboration, supporting the appropriate integration of minimally invasive strategies into modern cardiac care.

Keywords: minimally invasive cardiac surgery, MICS, coronary artery bypass grafting, mitral valve, aortic valve, congenital heart disease

Median sternotomy has long been the cornerstone of cardiac surgery, providing excellent exposure and reproducibility. Despite its effectiveness, sternotomy is associated with significant surgical trauma, postoperative pain, prolonged recovery, and potential complications such as sternal wound infection, mediastinitis, and delayed return to normal activities—particularly in elderly or high-risk patients.[1,2]

Minimally invasive cardiac surgery was developed to mitigate these drawbacks. By avoiding full sternal division and instead utilizing small thoracic incisions, partial sternotomy, or totally endoscopic access, MICS seeks to reduce invasiveness while preserving procedural safety and durability. Initially applied to selected valve and coronary procedures, minimally invasive techniques have expanded substantially over the past two decades.[3-8]

For non-surgeons and allied healthcare professionals, understanding MICS is increasingly important, as patients frequently inquire about "less invasive" surgical options. Moreover, appropriate referral and perioperative coordination depend on a clear appreciation of what MICS can and cannot offer.

What Can Be Done with Minimally Invasive Cardiac Surgery?

1. Coronary Artery Bypass Surgery

The modern evolution of off-pump coronary artery bypass grafting (OPCAB) and minimally invasive coronary surgery has been shaped by both technical innovation and sustained academic contributions from pioneering surgeons and institutions. Early reports by Buffolo and colleagues re-established the feasibility of direct myocardial revascularization without cardiopulmonary bypass, reintroducing beating-heart surgery as a viable surgical strategy.[9] Subsequent clinical studies further demonstrated favorable perioperative outcomes and accelerated recovery associated with OPCAB, particularly in selected patient populations, renewing interest in strategies that avoid the physiologic burden of extracorporeal circulation.[10]

The fundamental anatomic rationale for OPCAB lies in the epicardial location of the coronary arteries, which allows coronary anastomoses to be constructed on the beating heart without global myocardial ischemia or cardioplegic arrest (Figure 1). As awareness grew regarding the systemic consequences of cardiopulmonary bypass—including inflammatory activation, coagulopathy, myocardial ischemia, reperfusion injury, and subsequent organ dysfunction—OPCAB emerged not merely as a technical alternative, but as a physiologically sound strategy aimed at reducing procedure-related morbidity.[11-13] By avoiding cardiopulmonary bypass, OPCAB may attenuate systemic inflammatory responses, preserve native coagulation mechanisms, and support better preservation of cardiac, renal, pulmonary, and neurologic function, particularly in patients with limited physiologic reserve. Advances in stabilizing devices, intracoronary shunting, and exposure techniques have further enabled reproducible and complete revascularization while maintaining acceptable hemodynamic stability, supporting the role of OPCAB in appropriately selected patients when performed by experienced surgical teams.

Bangkok Heart Hospital has played a significant role in this global evolution. Under the leadership of Dr. Kit V. Arom, one of the early international pioneers of OPCAB and minimally invasive coronary surgery, the institution adopted OPCAB as its standard approach to coronary revascularization in 2001.[14-17] Since then, nearly all CABG procedures at the hospital have been performed using an off-pump technique. This long-term institutional commitment enabled the development of a focused and dedicated OPCAB program, allowing refinement of surgical techniques, perioperative management protocols, and patient selection strategies specific to beating-heart revascularization.

Dr. Arom's contributions extended beyond technical feasibility to the principles of complete and durable revascularization using OPCAB, including the treatment of multivessel coronary artery disease and high-risk populations such as patients with diabetes mellitus.[18] His work also laid the foundation for the adoption of minimally invasive and robotic-assisted coronary bypass surgery in Thailand, establishing Bangkok Heart Hospital as an early regional pioneer in Minimally invasive direct coronary artery bypass grafting (MIDCAB), robotic OPCAB, and beating-heart multivessel revascularization.[19]

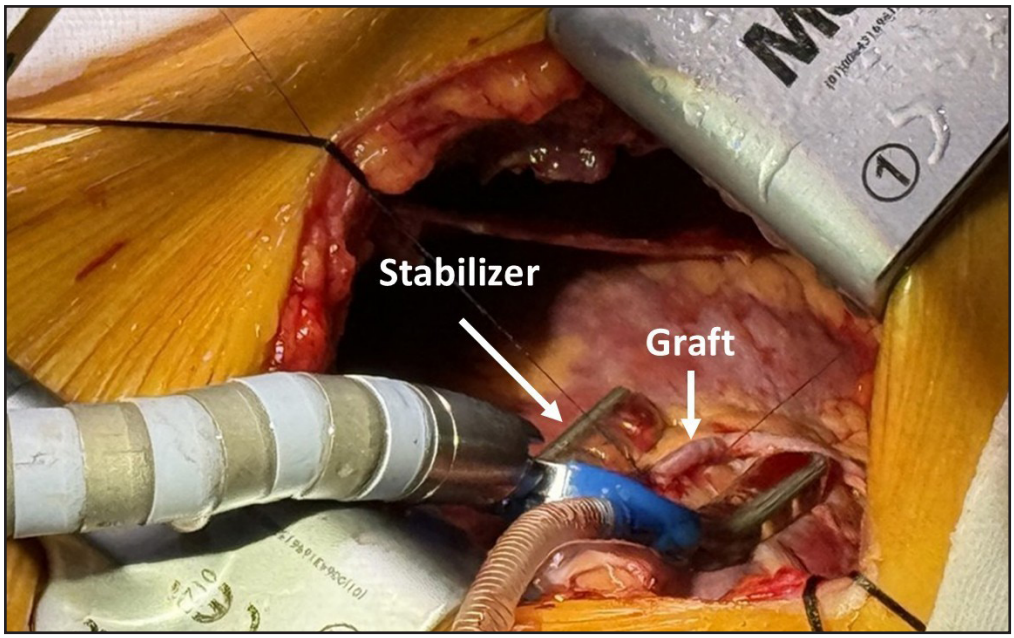


Figure 1: Technical Aspects of Minimally Invasive Off-Pump Coronary Artery Bypass Grafting (MICS-OPCAB) via Left Anterior Thoracotomy.
The image demonstrates intraoperative stabilization of the target coronary artery using a mechanical stabilizer, allowing precise distal anastomosis of the bypass graft under off-pump conditions. This technique enables effective myocardial revascularization through a limited left anterior thoracotomy without the use of cardiopulmonary bypass.

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Beyond surgical access and pump avoidance, long-term success in coronary artery bypass surgery is critically dependent on conduit selection and graft durability.[20] The Bangkok Heart Hospital group has made sustained academic contributions in this field, particularly in arterial grafting strategies. Foundational investigations involving the radial artery, internal thoracic artery, and total arterial revascularization—including comparative histopathologic analyses and randomized clinical outcome studies—clarified mechanisms of intimal hyperplasia, graft failure, and long-term patency.[21-27] These studies provided important evidence supporting the radial artery as a reliable second arterial conduit and contributed to the broader acceptance of arterial grafting in contemporary CABG practice.

More recent outcome-based analyses from the Bangkok Heart Hospital OPCAB cohort have focused on graft patency, long-term survival, and predictors of adverse outcomes. These studies demonstrated that outcomes after OPCAB are strongly influenced by conduit choice, patient selection, and perioperative management within a dedicated OPCAB program.[19,20] Importantly, these findings are consistent with international randomized trials, meta-analyses, and consensus statements, which emphasize that durable outcomes in OPCAB are achieved not by pump avoidance alone, but through meticulous surgical execution and strict adherence to fundamental revascularization principles.[28-32]

OPCAB has also served as a critical platform for the development of minimally invasive coronary surgery. The technical principles required for successful beating-heart revascularization—including target vessel stabilization, exposure of all coronary territories, and precise anastomotic technique—are directly transferable to Minimally invasive direct coronary artery bypass grafting (MIDCAB), MICS OPCAB, and robotic coronary bypass procedures. Early experience with totally endoscopic and robotic-assisted CABG at Bangkok Heart Hospital demonstrated feasibility, although initial adoption was limited by the technical complexity and constraints of early-generation instruments.[33]

With continued advancements in stabilizers, visualization systems, and conduit harvesting techniques, minimally invasive coronary surgery has matured substantially. At present, multivessel coronary revascularization using bilateral internal mammary arteries and composite arterial grafts can be performed through small thoracotomy incisions without sternotomy and without cardiopulmonary bypass.[34-36] The integration of minimal surgical access with a beating-heart strategy represents a logical progression toward what may be considered truly minimally invasive cardiac surgery for CABG (Figure 2).

Taken together, these academic and clinical contributions underscore a central principle supported by global evidence: successful OPCAB and minimally invasive CABG rely on surgical expertise and strict adherence to fundamental revascularization principles. The experience at Bangkok Heart Hospital illustrates how long-term institutional commitment to these principles enables the safe evolution of coronary surgery toward less invasive yet durable myocardial revascularization strategies.

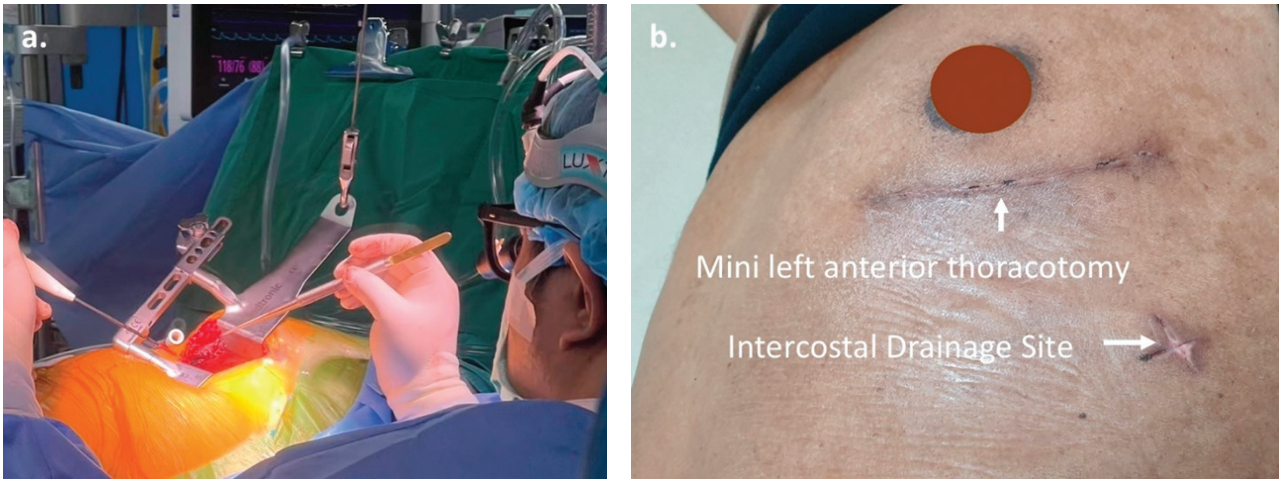


Figure 2: Surgical Access and Wound Healing After Minimally Invasive Off-Pump Coronary Artery Bypass Grafting via Left Anterior Thoracotomy
Minimally invasive cardiac surgery (MICS) demonstrating off-pump coronary artery bypass grafting (OPCAB) performed through a left anterior mini-thoracotomy. The intraoperative image (left) illustrates graft anastomosis via a limited anterior thoracotomy without cardiopulmonary bypass, while the postoperative image (right) shows the healed mini left anterior thoracotomy incision and the intercostal drainage site, highlighting reduced surgical trauma compared with conventional median sternotomy.

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2. Mitral Valve Surgery

Mitral valve surgery represents one of the most mature and extensively validated applications of minimally invasive cardiac surgery.[37] Over the past three decades, advances in endoscopic visualization, peripheral cardiopulmonary bypass strategies, myocardial protection, and refined repair techniques have enabled surgeons to perform complex mitral valve repair or replacement with outcomes comparable to, and in selected settings superior to, conventional median sternotomy.[38] High-definition endoscopic imaging, particularly with three-dimensional visualization, has enhanced intraoperative assessment of leaflet pathology, subvalvular structures, and coaptation geometry, thereby facilitating precise and reproducible repair strategies while minimizing surgical trauma.[39]

At Bangkok Heart Hospital, minimally invasive mitral valve surgery has evolved toward a fully endoscopic philosophy. All mitral valve procedures are performed using a totally endoscopic 3D approach, deliberately avoiding right anterior thoracotomy and direct vision techniques that require larger incisions and increased rib spreading. This approach minimizes chest wall trauma and intercostal nerve injury, which are key contributors to postoperative pain and delayed functional recovery. By relying exclusively on endoscopic visualization, the surgical field is magnified and uniformly illuminated, allowing meticulous execution of complex repair or replacement maneuvers through small access ports without compromising surgical exposure or precision (Figure 3).

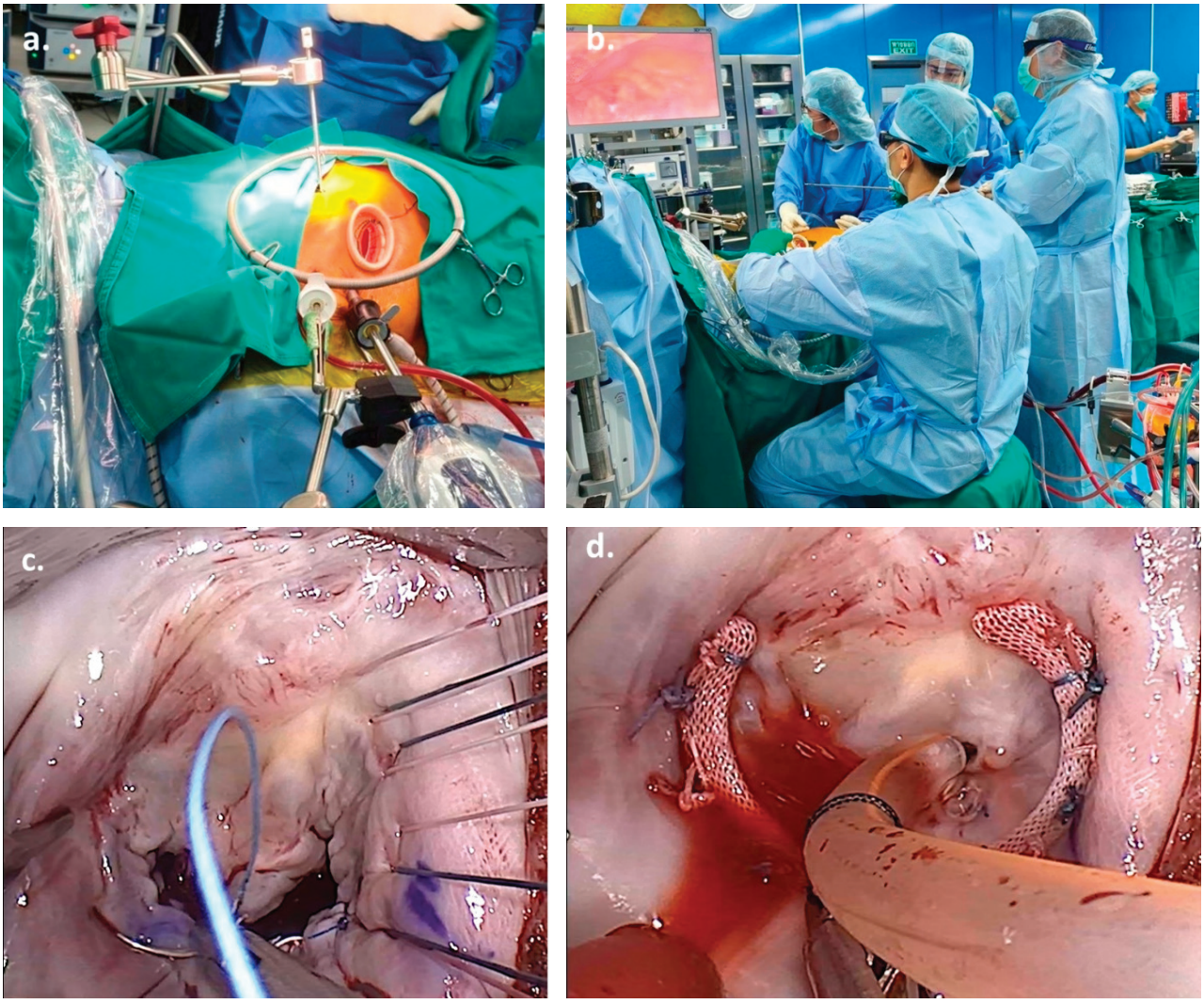


Figure 3: Totally Endoscopic Mitral Valve Repair.
Totally endoscopic mitral valve repair performed through a minimally invasive approach. Panels (a) and (b) demonstrate port placement and the operative setup with endoscopic visualization, while intraoperative endoscopic views (c, d) illustrate mitral valve exposure and repair, including leaflet correction and annuloplasty, achieved under high-definition thoracoscopic guidance without sternotomy.

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A distinctive feature of the program is the routine use of a periareolar incision in appropriately selected patients.[40] This access strategy permits mitral valve surgery through a very small skin incision while maintaining excellent internal visualization when combined with advanced endoscopic instrumentation.[41] Beyond its technical feasibility, the periareolar incision offers a substantial cosmetic advantage.[42] In most patients, the surgical scar becomes barely visible within two to three months after surgery, which significantly enhances patient satisfaction and body image perception. Importantly, this cosmetic benefit is achieved without increasing operative risk, operative time, or compromising the fundamental principles of mitral valve surgery (Figure 4).

From a pathological standpoint, both degenerative and rheumatic mitral valve diseases are suitable for a totally endoscopic surgical approach when appropriate patient selection and surgical expertise are present. Degenerative mitral regurgitation represents the most favorable substrate for minimally invasive mitral valve repair, as the underlying pathology—typically leaflet prolapse or flail due to chordal elongation or rupture—can be reliably addressed using established reconstructive techniques such as neochordal implantation and annuloplasty.[43] When performed within a structured and experienced totally endoscopic program, mitral valve repair for degenerative disease achieves high repair rates with excellent long-term durability. Importantly, outcomes are comparable to those of conventional sternotomy-based surgery, underscoring that surgical success is primarily driven by adherence to classical mitral repair principles rather than the surgical access itself. These findings are consistent with contemporary registry data and reinforce minimally invasive endoscopic repair as a mature and reproducible strategy for degenerative mitral valve disease.[43]

Rheumatic mitral valve disease poses distinct pathological and technical challenges for valve repair. Although repair may be feasible in carefully selected patients—particularly those with so-called "burnt-out" rheumatic disease and preserved leaflet pliability—long-term durability is frequently limited by progressive leaflet fibrosis, calcification, commissural fusion, and subvalvular restriction.[44,45] Contemporary series from experienced centers suggest that, with strict intraoperative echocardiographic quality control and meticulous adherence to repair principles, durable repair may be achievable in selected adult patients; however, feasibility decreases and repair complexity increases with advancing pathology.[46,47] Consequently, mitral valve replacement is often favored in advanced rheumatic disease to ensure durable correction. A recent high-value care systematic review and meta-analysis demonstrated that while rheumatic mitral repair may be associated with lower early mortality and improved long-term survival in selected cohorts, these benefits must be balanced against the risk of late structural deterioration and reintervention.[48] Importantly, rheumatic pathology does not preclude a minimally invasive approach. Totally endoscopic mitral valve replacement can be performed safely and reproducibly, preserving the advantages of reduced surgical trauma, faster recovery, and improved patient experience, provided that patient selection is guided by sound surgical principles and the ability to achieve adequate exposure, myocardial protection, and durable repair or replacement.[44–48]

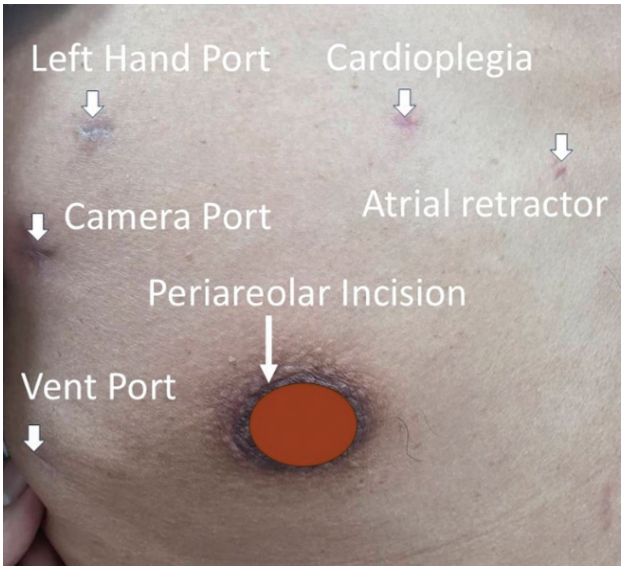


Figure 4: Surgical Incision for a Totally Endoscopic Cardiac Surgery for Mitral Valve surgery and Closure of Atrial Septal Defect. *Postoperative surgical incisions 8 weeks after surgery following totally endoscopic cardiac surgery for mitral valve surgery and atrial septal defect closure. The long arrow indicates a periareolar incision used as the main working port, while the short arrows denote multiple small auxiliary port sites for the aortic cross-clamp, cardioplegia cannula, atrial retractor, and endoscopic instruments, demonstrating excellent wound healing and favorable cosmetic outcomes with a minimally invasive access strategy.*

The totally endoscopic approach aligns naturally with enhanced recovery after surgery (ERAS) principles for valve surgery. Reduced surgical trauma, smaller incisions, and avoidance of rib spreading contribute to lower postoperative pain, reduced opioid requirements, and earlier mobilization. When combined with multimodal analgesia, early extubation strategies, goal-directed fluid therapy, and structured physiotherapy, minimally invasive mitral surgery facilitates faster functional recovery and shorter hospital length of stay without compromising safety. These benefits are increasingly recognized as integral components of high-quality valve surgery rather than secondary advantages.

Equally important, minimally invasive access should not be equated with limited surgical ambition. Complex mitral valve repairs, multisegment disease, concomitant tricuspid valve procedures, atrial septal defect closure, and surgical ablation for atrial fibrillation can all be accomplished through a totally endoscopic approach in experienced hands. The defining factor for success remains strict adherence to fundamental reconstructive principles, including restoration of leaflet mobility, creation of a broad and stable coaptation surface, and appropriate annular remodeling to ensure long-term valve competence.

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In this context, the experience at Bangkok Heart Hospital illustrates that minimally invasive mitral valve surgery represents not merely an alternative incision but a comprehensive, patient-centered surgical strategy. By integrating totally endoscopic 3D visualization, refined peripheral perfusion techniques, and evidence-based perioperative care pathways, excellent clinical outcomes can be achieved alongside meaningful improvements in recovery, cosmesis, and overall patient experience. This evolution reflects the modern direction of mitral valve surgery, where durable repair or replacement and enhanced recovery are pursued simultaneously as complementary goals.

3. Aortic Valve Surgery

Over the past two decades, aortic valve surgery has undergone a progressive evolution driven by the desire to reduce operative trauma while preserving the durability, safety, and reproducibility of surgical aortic valve replacement (SAVR). This evolution has led to the widespread adoption of minimally invasive aortic valve replacement (MIAVR), most commonly performed through right anterior minithoracotomy or partial upper ministernotomy.[49] These approaches were initially developed as alternatives to full sternotomy but have since matured into established surgical strategies supported by robust clinical evidence and growing institutional experience.[50,51]

Both right anterior minithoracotomy and ministernotomy are performed under general anesthesia with comprehensive hemodynamic monitoring, routine transesophageal echocardiography, and full cardiopulmonary bypass. Importantly, the principle of surgical safety remains paramount: readiness for rapid conversion to full sternotomy is mandatory, and operating room setup closely mirrors that of conventional SAVR. When performed in experienced centers, these minimally invasive approaches have demonstrated reproducible reductions in postoperative pain, respiratory complications, transfusion requirements, and length of hospital stay, without compromising operative mortality, valve hemodynamics, or long-term survival.

The right anterior minithoracotomy approach provides access to the aortic valve through a small intercostal incision, typically avoiding sternal division altogether. Adequate exposure of the ascending aorta and aortic root is achieved through meticulous patient positioning, pericardial traction, and careful assessment of thoracic anatomy. Peripheral cannulation strategies, often via the femoral vessels, facilitate cardiopulmonary bypass while maintaining a limited operative field. Despite the reduced incision size, advances in myocardial protection, endoscopic visualization, and suturing technology have enabled precise valve excision, complete annular decalcification, and secure prosthesis implantation. As surgeon experience increases, operative times and technical complexity approach those of conventional surgery.[52]

The partial upper ministernotomy, most commonly performed as a J-shaped incision, represents a balanced compromise between reduced invasiveness and conventional exposure. Preservation of the lower sternum maintains chest wall stability while providing direct access to the ascending aorta.[53] A key advantage of this approach is its flexibility: central cannulation, standard myocardial protection strategies, and familiar instrumentation can all be employed, and conversion to full sternotomy can be achieved rapidly if required. This makes ministernotomy particularly attractive in elderly patients, redo surgery, or cases with uncertain anatomy, while still conferring the benefits of reduced surgical trauma.

Beyond these established MIAVR techniques, totally endoscopic aortic valve replacement (TEAVR) has emerged as the most advanced expression of minimally invasive surgical aortic valve surgery. TEAVR eliminates direct vision through a thoracotomy or sternotomy incision, relying instead on high-definition endoscopic visualization and specialized long-shaft instruments. Through small working ports and a limited access incision, surgeons can perform complete aortic valve excision and replacement under full cardiopulmonary bypass with cardioplegic arrest (Figure 5). Early series have demonstrated the technical feasibility and safety of TEAVR in selected patients, with low mortality, acceptable cross-clamp times, and favorable early hemodynamic results.[54,55]

Importantly, recent experience has shown that even complex surgical maneuvers traditionally considered incompatible with minimally invasive access—such as aortic root enlargement—can be performed in a totally endoscopic fashion. Totally endoscopic AVR combined with aortic root enlargement has been reported as a viable strategy to prevent patient–prosthesis mismatch in patients with a small aortic annulus, allowing implantation of larger prosthetic valves while preserving the benefits of minimal access surgery.[56] Although cardiopulmonary bypass and cross-clamp times are longer, early outcomes suggest that this approach may expand the indications of TEAVR and enhance its relevance in younger patients or those requiring optimal long-term valve hemodynamics.[57]

Despite its promise, TEAVR remains technically demanding and is currently concentrated in highly specialized centers with extensive experience in minimally invasive and endoscopic cardiac surgery. The steep learning curve, need for dedicated instrumentation, and reliance on a coordinated multidisciplinary team underscore the importance of careful patient selection and institutional readiness. Nevertheless, TEAVR represents a logical extension of the minimally invasive surgical philosophy and highlights the ongoing innovation within surgical aortic valve therapy.

The contemporary role of MIAVR and TEAVR must be interpreted within a broader therapeutic landscape that now includes transcatheter aortic valve implantation (TAVI). Randomized trials such as PARTNER 3 and Evolut Low Risk

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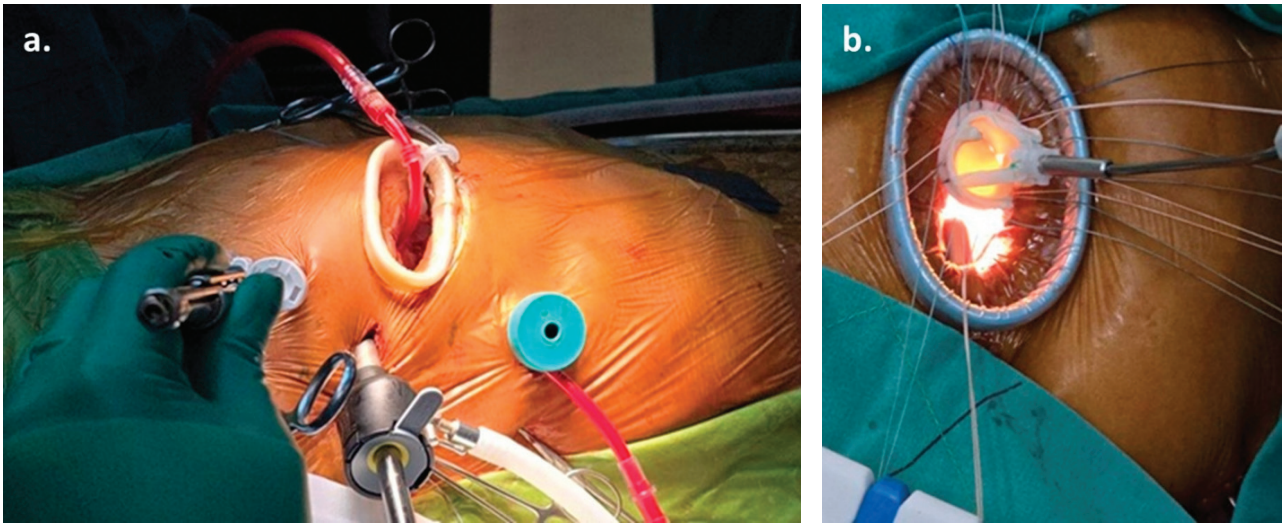


Figure 5: Totally Endoscopic Aortic Valve Replacement (TEAVR)
Totally endoscopic aortic valve replacement (TEAVR) performed through a minimally invasive approach. Panel (a) illustrates peripheral cardiopulmonary bypass cannulation and strategic port placement via a limited thoracic access, while panel (b) demonstrates the endoscopic operative field during aortic valve replacement using specialized minimally invasive instruments under high-definition thoracoscopic visualization.

have established the safety and efficacy of TAVI in patients with symptomatic severe aortic stenosis at low surgical risk, leading to guideline recommendations favoring transcatheter therapy in selected elderly patients with suitable anatomy.[58-61] In addition to clinical outcomes, economic analyses have demonstrated that TAVI can be highly cost-effective in specific healthcare systems, particularly when early recovery and quality-of-life gains are emphasized.[62]

However, population-level cost-effectiveness does not diminish the enduring value of surgical aortic valve replacement. Surgical AVR—whether performed via full sternotomy, MIAVR, or TEAVR—offers unmatched versatility in addressing complex pathology, including bicuspid valves, pure aortic regurgitation, extensive annular or left ventricular outflow tract calcification, and the need for concomitant cardiac procedures. Furthermore, concerns regarding long-term durability, coronary access, and lifetime management strategies remain central considerations in younger patients and those with long life expectancy.

In this context, MIAVR occupies a critical intermediate position between conventional full sternotomy and transcatheter therapy, while TEAVR represents the frontier of surgical minimalism. Together, these approaches allow surgeons to preserve the fundamental principles of surgical valve replacement—complete excision, meticulous annular preparation, and secure prosthesis implantation—while minimizing surgical trauma and enhancing postoperative recovery. Crucially, these benefits are realized without compromising procedural safety or long-term outcomes when performed within structured programs by experienced teams.

Regardless of the chosen technique[63], intraoperative imaging plays a pivotal role in ensuring procedural success. Transesophageal echocardiography provides immediate assessment of prosthetic valve position, leaflet motion, transvalvular gradients, effective orifice area, and paravalvular regurgitation following separation from cardiopulmonary bypass. These evaluations are essential across the entire spectrum of surgical and transcatheter therapies and reinforce the shared goal of optimal valve performance.

In summary, aortic valve surgery has evolved into a spectrum of complementary strategies rather than competing modalities within a contemporary heart team framework. Full sternotomy SAVR, minimally invasive AVR (MIAVR), totally endoscopic AVR (TEAVR), and transcatheter aortic valve implantation (TAVI) represent distinct yet overlapping options, each occupying a specific role in modern aortic valve care. Treatment selection has therefore become increasingly nuanced and multidimensional, extending beyond a binary surgical–transcatheter paradigm to incorporate typical clinical indications, valve pathology suitability, access and incision, use of cardiopulmonary bypass, expected valve durability, early recovery profiles, and the ideal clinical niche for each approach. In this context, **Table 1** provides a structured comparative overview of these key attributes, supporting balanced heart team deliberations and individualized decision-making. Collectively, these strategies enable tailored treatment of aortic valve disease while preserving surgical durability, procedural safety, and patient-centered care.

This integrative philosophy naturally extends beyond acquired aortic valve disease and provides a foundation for subsequent sections of this review. As minimally invasive

Table 1: Comparison of Aortic Valve Replacement Strategies.

Aspect	TAVI	MIAVR	TEAVR	Conventional SAVR (Full Sternotomy)
Typical Indications	• Elderly patients (≥75 yrs) • Symptomatic severe AS • Suitable transfemoral anatomy, • Rapid recovery priority	• AS or AR, • Low–intermediate risk • Unsuitable for TAVI • Desire reduced invasiveness with durability	• Selected AS/AR in expert centers • Patients desiring minimal access with surgical valve durability	• All valve pathologies • Young patients • Complex anatomy • Combined procedures
Valve Pathology Suitability	• Best for tricuspid AS; Limited for pure AR/bicuspid	• AS and AR; Bicuspid feasible	• AS and AR; Selected bicuspid feasible	• Universal applicability
Access / Incision	• Percutaneous (usually transfemoral)	• Partial sternotomy or right anterior minithoracotomy	• Totally endoscopic ports + small working incision	• Full median sternotomy
Cardiopulmonary Bypass	• No	• Yes	• Yes	• Yes
Valve Durability	• Mid-term robust; long-term evolving	• Excellent long-term durability	• Excellent long-term durability	• Excellent long-term durability
Early Recovery	• Fastest	• Faster than full sternotomy	• Similar or faster than MIAVR	• Slowest
Ideal Clinical Niche	• Elderly with favorable anatomy prioritizing minimal invasiveness	• Surgical candidates desiring reduced trauma	• Highly selected patients in expert centers	• Young patients, complex disease

TAVI = transcatheter aortic valve implantation, MIAVR = minimally invasive aortic valve replacement, TEAVR = totally endoscopic aortic valve replacement, SAVR = surgical aortic valve replacement, AS = Aortic Stenosis, AR = Aortic Regurgitation

principles are increasingly applied to congenital heart disease, hybrid procedures, and future technological developments, the boundaries between traditional surgical and transcatheter domains continue to blur. Congenital and structural interventions now frequently incorporate hybrid strategies that combine surgical access with catheter-based techniques, while advances in imaging, instrumentation, and simulation are reshaping training pathways and expanding the scope of minimally invasive cardiac surgery.

In the sections that follow, attention will shift toward these emerging domains, including minimally invasive approaches in congenital heart disease, hybrid procedures that leverage the strengths of both surgical and transcatheter therapies, and future directions in cardiac surgery driven by technological innovation. Together, these developments reflect a unifying theme: the ongoing transformation of cardiac surgery toward patient-centered, anatomy-driven, and sustainability-conscious care, where technique selection is guided not by tradition alone but by a thoughtful synthesis of evidence, expertise, and evolving patient expectations.

4. Congenital and Other Cardiac Procedures

Minimally invasive cardiac surgery has emerged as a credible and increasingly mature alternative to median sternotomy for selected congenital and other right-sided cardiac procedures in adults. Contemporary evidence consistently demonstrates that the cosmetic and musculoskeletal advantages of sternal-sparing access can be achieved without compromising repair quality, procedural safety, or mid- to long-term durability when appropriate patient selection and experienced multidisciplinary teams are in place.[64]

Among adult congenital lesions, atrial septal defect (ASD) repair—particularly secundum ASD—represents the most widely adopted minimally invasive application. Right-sided mini-thoracotomy approaches, including anterolateral, vertical infra-axillary, and mid-axillary incisions, provide direct access to the right atrium with excellent visualization for patch closure while avoiding sternal division and reducing wound morbidity. Large contemporary reviews and institutional series report perioperative mortality rates comparable to conventional sternotomy and very low conversion rates when anatomical suitability and team experience are respected. Although operative times may be modestly longer early in the learning curve, this difference consistently attenuates after approximately 15-20 consecutive cases per surgeon as programs standardize patient positioning, exposure, and perfusion workflows.[65,66]

Endoscopic and totally endoscopic techniques—with or without robotic assistance—have further extended the minimally invasive paradigm to ASD repair in older children and adults. These approaches typically rely on three to four trocar ports and predominantly peripheral cannulation to declutter the operative field and enhance visualization. Published series demonstrate feasibility and safety in carefully selected patients, with excellent cosmetic outcomes and low complication rates. However, the need for specialized infrastructure, advanced imaging, and structured team training currently limits widespread adoption, confining these techniques largely to experienced, high-volume centers.[65,67]

Beyond ASD repair, minimally invasive access has been successfully applied to a broader spectrum of congenital and acquired right-sided cardiac procedures. Tricuspid valve repair is particularly well suited to right thoracotomy exposure, as the valve apparatus aligns naturally with the surgeon's line of

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sight through a small intercostal window. In adult congenital cohorts, sternal sparing has been associated with faster functional recovery and fewer wound-related complications, provided that bicaval control, myocardial protection, and intracardiac exposure are meticulously orchestrated within the constrained operative field. Similarly, atrial tumor excision—including myxoma resection—can be performed safely through minimally invasive access, allowing en bloc removal and careful de-airing. Experienced teams often employ carbon dioxide insufflation and low-profile instrumentation to maintain visualization and minimize the risk of air embolism, reflecting techniques refined within pediatric minimally invasive practice and effectively translated to adult anatomy.[65,67]

Cardiopulmonary bypass strategies are a critical enabler of success in minimally invasive congenital surgery and must be individualized according to anatomy, body size, and lesion complexity. Both central and peripheral cannulation approaches have been applied safely, with no consistent superiority of one strategy over another across centers.[68] Instead, outcomes are determined by reproducible team workflows, thorough preoperative imaging to delineate venous anomalies or anomalous pulmonary venous connections, and readiness to adapt cannulation strategies intraoperatively as required.[65,67]

Concerns regarding potential trade-offs between cosmesis and safety have been addressed by contemporary outcome data. Across large minimally invasive congenital series, cumulative mortality remains extremely low and comparable to conventional sternotomy, while complication profiles—including postcardiotomy syndrome and pleural or pericardial effusions—are similar.[69,70] Postoperative recovery metrics frequently favor minimally invasive approaches, with shorter ventilation times, reduced chest drainage, and shorter intensive care and hospital length of stay in matched analyses, although the limitations of retrospective design and selection bias must be acknowledged. Importantly, patient-reported outcomes—including body image, activity resumption, and scar concealment—continue to improve over months, reinforcing minimally invasive access as a patient-centered option when repair completeness is uncompromised.[65,66]

Pain trajectories merit balanced interpretation. Thoracotomy-related neuropathic pain is a recognized entity in thoracic surgery; however, contemporary congenital series suggest that with muscle-sparing access, careful intercostal nerve protection, and modern perioperative analgesia pathways, chronic pain rates are comparable to or lower than those reported after median sternotomy. Conversely, chronic post-sternotomy pain remains underappreciated, underscoring that sternal sparing adds value beyond aesthetics alone. In women, incision selection deserves particular attention: axillary or mid-axillary access is generally preferred over submammary incisions in younger patients to preserve long-term cosmesis without compromising exposure.[65,66]

Redo operations represent another domain in which minimally invasive strategies have matured. In experienced centers, selected redo congenital repairs—such as sinus venosus ASD or partial anomalous pulmonary venous drainage—can be performed through subaxillary or right thoracotomy approaches. Preoperative computed tomography angiography, three-dimensional reconstructions, and, when necessary, pre-emptive peripheral cardiopulmonary bypass for safe re-entry reduce conversion risk and enhance procedural safety.[66,67,71]

Collectively, these developments reflect a broader conceptual shift from "minimally invasive" as a descriptor of incision size to "minimal-impact surgery" as a comprehensive care philosophy. This perspective emphasizes reduced transfusion requirements, minimized adhesions for future interventions, and proactive planning for catheter-based valve-in-valve or hybrid procedures as patients age—an especially relevant paradigm in adult congenital heart disease. Programmatic success depends on multidisciplinary commitment, proctored training, standardized algorithms, and rigorous outcomes auditing. Looking forward, expanded use of endoscopic assistance, hybrid congenital interventions, and advanced imaging for personalized access planning is likely to further broaden the scope of minimally invasive congenital cardiac surgery.

How Is Minimally Invasive Cardiac Surgery Performed?

Minimally invasive cardiac surgery (MICS) is not defined by a single incision or technology, but rather by an integrated operative strategy that combines alternative surgical access, advanced visualization, tailored cardiopulmonary bypass techniques, and multidisciplinary perioperative coordination. The central aim is to reduce surgical trauma while preserving the fundamental principles of cardiac surgery—complete correction of pathology, procedural safety, and long-term durability. International consensus statements and long-term institutional experiences consistently emphasize that minimally invasive approaches should replicate, not compromise, the standards established by conventional sternotomy-based surgery.[72]

Surgical access is obtained through small thoracic incisions, partial sternotomy, or fully endoscopic port-based approaches, selected according to the target pathology, patient anatomy, and institutional expertise. Common access routes include right anterior or lateral mini-thoracotomy, upper J-shaped ministernotomy, infra-axillary incisions, and totally endoscopic configurations using three- or four-port techniques. Importantly, incision selection is guided by exposure requirements, ergonomic instrument alignment, and safe conduct of cardiopulmonary bypass rather than cosmetic considerations alone. The literature consistently underscores that readiness for immediate conversion to full sternotomy remains a core safety principle and a defining feature of mature MICS programs.[8,72]

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Limited access is compensated by enhanced visualization technologies. High-definition and three-dimensional endoscopic imaging provide magnified, en-face views of intracardiac structures, enabling precise leaflet assessment, annular work, and suture placement. Comparative studies involving single- and multiple-valve procedures demonstrate that, when performed in experienced centers, endoscopic and minimally invasive approaches achieve operative mortality, repair quality, and mid-term outcomes comparable to median sternotomy, despite longer operative or cross-clamp times early in the learning curve.[73]

Cardiopulmonary bypass remains integral to most minimally invasive cardiac operations. Cannulation strategies include central, peripheral, or hybrid configurations and are tailored to incision type, pathology, and vascular anatomy.[74-79] Peripheral femoral cannulation is frequently employed to declutter the operative field in thoracotomy and endoscopic procedures, whereas central cannulation is commonly used in ministernotomy approaches to preserve familiarity and simplify myocardial protection. Large series and consensus reviews indicate that no single cannulation strategy is universally superior; instead, outcomes depend on standardized workflows, meticulous imaging guidance, and coordinated team execution.[8,72]

Myocardial protection strategies are similarly adapted to limited access.[80] Antegrade cardioplegia remains the mainstay, with selective ostial delivery in the presence of significant aortic regurgitation and adjunctive retrograde cardioplegia when appropriate. Carbon dioxide insufflation, controlled ventricular filling, and structured de-airing protocols under continuous transesophageal echocardiographic guidance are essential, particularly in totally endoscopic procedures. These principles, originally refined in minimally invasive mitral and congenital surgery, have translated effectively across the broader MICS spectrum.

Anesthetic management is a critical enabler of minimally invasive surgery. One-lung ventilation facilitates exposure in thoracotomy and endoscopic approaches, while advanced hemodynamic monitoring and continuous transesophageal echocardiography guide cannulation, myocardial protection, and immediate assessment of procedural results. Close coordination among surgeons, anesthesiologists, and perfusionists is particularly vital during key phases such as cannulation, cross-clamping, de-airing, and separation from cardiopulmonary bypass.

Postoperative management increasingly incorporates enhanced recovery after surgery (ERAS) principles adapted to minimally invasive cardiac procedures.[81-83] Multimodal analgesia, early extubation, prompt mobilization, and restrictive transfusion strategies contribute to reduced ventilation times, shorter intensive care and hospital stays, and faster functional recovery. These benefits reinforce that the impact of MICS extends beyond the operative field to the entire perioperative pathway.

Importantly, the technical feasibility of minimally invasive cardiac surgery does not equate to universal applicability. Each component described above—access, visualization, cannulation, myocardial protection, and perioperative management—imposes specific anatomical and physiological requirements. Consequently, optimal outcomes depend not only on surgical technique but also on careful patient selection and multidisciplinary decision-making. This transition from technical execution to individualized applicability forms the foundation of the following section.

Patient Selection

Appropriate patient selection remains the cornerstone of successful minimally invasive cardiac surgery (MICS). The benefits of reduced surgical access can only be realized when anatomical feasibility, procedural complexity, and patient-specific risk factors are carefully balanced against the limitations imposed by restricted exposure. Early experience with minimally invasive and off-pump techniques has consistently demonstrated that outcomes are driven less by incision size and more by judicious case selection and disciplined adherence to fundamental surgical principles.[84]

Ideal candidates for MICS are patients with isolated or straightforward cardiac pathology, favorable thoracic and vascular anatomy, and limited comorbid burden. Degenerative mitral valve disease with repairable anatomy, isolated left anterior descending artery disease amenable to minimally invasive direct coronary artery bypass, and isolated aortic valve pathology without extensive annular or aortic calcification represent classic indications in contemporary practice. These patients derive the greatest benefit from reduced surgical trauma, shorter recovery, and faster functional restoration, while maintaining procedural safety and durability.

Conversely, certain patient subsets warrant caution or exclusion from minimally invasive approaches. Severe peripheral vascular disease may preclude safe peripheral cannulation; extensive ascending aortic calcification increases embolic risk; advanced chronic obstructive pulmonary disease may limit tolerance of single-lung ventilation; and complex multivalvular or combined procedures can negate the advantages of limited access. Importantly, these considerations echo early foundational work in minimally invasive coronary surgery, which emphasized that compromised exposure, poor target quality, or excessive physiological stress undermines procedural success and should prompt conversion to a more conventional approach rather than persistence with a limited incision.[85]

Patient selection is not static but evolves with institutional experience and technical maturity. Data from mitral valve surgery highlight that as teams progress along the learning curve, selection criteria broaden cautiously, incorporating higher-risk patients while maintaining acceptable outcomes—provided repair quality is not compromised.[86,87] Nonetheless, the guiding principle remains unchanged:

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minimally invasive surgery should never be pursued at the expense of safety, completeness of repair, or long-term durability.

A multidisciplinary heart team discussion is therefore indispensable. Surgeons, cardiologists, anesthesiologists, imaging specialists, and perfusionists collectively evaluate anatomical suitability, procedural alternatives (including transcatheter or hybrid strategies), and patient priorities. This collaborative framework ensures that the choice of a minimally invasive approach reflects an individualized risk–benefit assessment rather than a default preference for smaller incisions.

In this context, patient selection serves as the conceptual bridge between how minimally invasive cardiac surgery is performed and why it confers meaningful advantages. When applied appropriately, careful selection amplifies the clinical and patient-centered benefits described in the following section.

Benefits of Minimally Invasive Cardiac Surgery

The benefits of minimally invasive cardiac surgery extend well beyond cosmetic considerations and are best understood as the downstream consequence of reduced surgical trauma combined with preserved procedural integrity. When patient selection is appropriate and core surgical principles are rigorously maintained, minimally invasive cardiac surgery (MICS) offers consistent advantages across perioperative recovery, functional outcomes, health-related quality of life, and healthcare resource utilization.

From a physiological standpoint, smaller incisions and avoidance of full median sternotomy translate into reduced musculoskeletal disruption, lower postoperative pain scores, and a diminished systemic inflammatory response. Multiple observational studies and propensity-matched analyses have demonstrated reduced intraoperative blood loss and lower transfusion requirements compared with conventional sternotomy, particularly in isolated mitral valve surgery and minimally invasive coronary bypass procedures. These perioperative advantages contribute directly to shorter mechanical ventilation times, reduced intensive care unit stay, and earlier mobilization without compromising operative safety.[72,73]

Enhanced recovery trajectories represent one of the most consistently reported advantages of MICS. Patients undergoing minimally invasive mitral valve surgery or minimally invasive coronary artery bypass frequently experience shorter total hospital length of stay and a faster return to baseline functional status. Importantly, these benefits are not achieved at the expense of increased operative mortality, stroke, or compromised repair durability when surgery is performed in experienced centers. This finding has been reinforced across both valve and coronary literature and supports the concept that surgical quality is preserved despite reduced access.[72,85]

Beyond traditional clinical endpoints, health-related quality of life (HRQoL) has emerged as a critical metric in contemporary cardiac surgery evaluation. Studies specifically examining HRQoL after minimally invasive cardiac surgery demonstrate earlier and more pronounced improvements in physical functioning, role limitation, bodily pain, and social activity compared with conventional sternotomy. These benefits are most evident in the early postoperative period but often persist for several months, reflecting faster functional recovery and reduced physical restriction rather than purely cosmetic satisfaction.[88] Patients report less discomfort during daily activities, improved sleep quality, and greater confidence in resuming normal life roles, reinforcing the patient-centered value of minimally invasive approaches.

From the patient perspective, these quality-of-life gains translate into an earlier return to work, reduced reliance on opioid and non-opioid analgesics, and improved overall satisfaction with the surgical experience. This is particularly relevant for younger and working-age patients, for whom prolonged sternal precautions following full sternotomy may impose substantial occupational and social limitations. Even in older patients, improved early mobility and independence can reduce deconditioning and facilitate smoother transitions to home or rehabilitation settings.[88]

At the healthcare system level, minimally invasive approaches may offer advantages in resource utilization when implemented within structured, high-volume programs. Although operative times may be longer during the early learning curve, these differences tend to diminish as surgical teams standardize positioning, cannulation strategies, and operative workflows. Reduced length of stay, lower transfusion rates, and fewer wound-related complications can offset increased procedural complexity and equipment requirements, supporting favorable cost-effectiveness profiles in experienced centers.[72,85]

Importantly, the benefits of MICS should not be interpreted as universal or automatic. Rather, they are conditional advantages that depend on careful patient selection, surgeon experience, institutional volume, and coordinated perioperative management. When these elements are aligned, minimally invasive cardiac surgery fulfills the broader concept of "minimal impact surgery," emphasizing durable outcomes, patient safety, and long-term value rather than incision size alone.

Together, the demonstrable perioperative, functional, and quality-of-life benefits outlined in this section build directly upon the principles of patient selection discussed in Section 3 and provide essential context for understanding the risks, limitations, and future directions of minimally invasive cardiac surgery addressed in the subsequent sections.

Risks and Limitations of Minimally Invasive Cardiac Surgery

Despite its well-recognized benefits, minimally invasive cardiac surgery (MICS) is associated with specific risks and limitations that warrant careful consideration. Peripheral cannulation, which is frequently required in minimally invasive approaches, carries a potential risk of vascular injury, limb ischemia, or embolic complications, particularly in patients with advanced peripheral arterial disease or unfavorable iliofemoral anatomy.[89,90] In addition, restricted operative exposure and reliance on endoscopic or video-assisted visualization demand advanced technical skills and meticulous coordination among the surgical, anesthesia, and perfusion teams.[91,92]

The learning curve for MICS is substantial and extends beyond the operating surgeon alone to encompass the entire multidisciplinary team. Contemporary analyses emphasize that minimal access does not automatically translate into reduced physiological stress; prolonged cardiopulmonary bypass or aortic cross-clamp times during the early learning phase may attenuate the expected benefits of smaller incisions.[8,89] These observations underscore the importance of structured training, proctorship, and simulation-based education to ensure patient safety during program development.

Conversion to full sternotomy may be required in selected cases to address unexpected bleeding, inadequate exposure, or hemodynamic instability. Such conversion should be regarded as a deliberate safety strategy rather than a procedural failure. Clear preoperative counseling and informed consent remain essential, allowing patients to understand that the primary objective of minimally invasive surgery is optimal clinical outcome, not incision size alone.[72]

Recognition of these limitations provides a rational framework for responsible innovation and guides the future evolution of minimally invasive cardiac surgery.

Future Directions in Minimally Invasive Cardiac Surgery

The future of minimally invasive cardiac surgery is increasingly driven by technological advancement and multidisciplinary integration. Robotic platforms, high-definition three-dimensional visualization, and refined endoscopic instrumentation continue to expand the technical feasibility and precision of minimal-access procedures across valve and coronary domains.[93-97] Parallel developments in imaging—including preoperative CT-based access planning and intraoperative fusion imaging—are improving procedural predictability and safety.[71,98]

Hybrid surgical–interventional strategies represent another important frontier, allowing tailored treatment pathways that combine the durability of surgical repair with the reduced invasiveness of catheter-based therapies. In parallel, artificial intelligence and data-driven decision support systems are expected to enhance patient selection, procedural planning, and outcome prediction, supporting more personalized care.[93,99]

Equally important, the expansion of standardized training curricula, simulation-based assessment, and formal credentialing pathways is likely to facilitate broader and safer adoption of MICS beyond high-volume centers. These developments collectively signal a shift from technique-driven innovation toward systems-based optimization of minimally invasive cardiac care.[89]

As these innovations mature, the central challenge will be to align technological progress with durable outcomes, evidence-based practice, and patient-centered values.

Conclusion

Minimally invasive cardiac surgery represents a significant evolution in contemporary cardiovascular care. When applied to appropriately selected patients and performed by experienced multidisciplinary teams, it achieves excellent clinical outcomes while offering meaningful advantages in postoperative recovery, comfort, and quality of life.[72,89]

The future of cardiac surgery is defined not solely by smaller incisions, but by intelligent integration of surgical principles, advanced technology, and individualized treatment strategies. A comprehensive understanding of indications, techniques, benefits, and limitations is therefore essential for clinicians navigating this rapidly advancing field and for ensuring that minimally invasive approaches continue to enhance—rather than compromise—patient safety, durability of repair, and long-term clinical value.[93]

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