

Review

Robotic Mitral Valve Repair: Contemporary Evidence, Clinical Outcomes, and Implementation Considerations

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Academic Editor: Giuseppe Santarpino

Submitted: 3 March 2026 Revised: 30 May 2026 Accepted: 11 June 2026 Published: 10 October 2026

Abstract

Robotic mitral valve surgery (RMVS) is increasingly used as a minimally invasive approach for mitral intervention in specialist centres. This narrative review summarizes contemporary evidence from matched observational studies, national database analyses, and meta-analyses comparing RMVS with sternotomy and mini-thoracotomy approaches, with emphasis on perioperative outcomes, repair quality, durability, learning curves, program implementation, and cost. In experienced programmes, RMVS is associated with high repair rates, low mortality and morbidity, with shorter intensive care unit and hospital stays and faster postoperative recovery than sternotomy-based pathways. Operative, cardiopulmonary bypass, and aortic cross-clamp times are generally longer, particularly during early adoption, but improve with cumulative experience and workflow standardization. Economic findings are less consistent, with reported costs ranging from equivalent to higher than conventional approaches depending on case volume, analytic perspective, and treatment of capital expenditure. Successful implementation depends on careful patient selection, multidisciplinary team training, dedicated infrastructure, and prospective quality oversight. Important limitations of the current evidence base include the predominance of observational data, centre-volume effects and whether this technology is applicable in low volume programs, robust health-economic evaluation in resource-constrained systems and limited direct comparison with totally endoscopic non-robotic mitral surgery. Overall, RMVS is a very safe and effective approach for mitral intervention when delivered within an experienced, protocol-driven programme.

Keywords: mitral valve surgery; minimally invasive surgery; robotic mitral valve repair; evidence; outcomes; implementation

1. Introduction

Mitral regurgitation (MR) is the most common form of valvular heart disease, affecting more than 24 million people worldwide. Over the past three decades, mitral valve (MV) reconstructive surgery has advanced substantially, with repair now recognized as the preferred treatment for degenerative disease when durable reconstruction is feasible, restoring long-term survival towards that of an age- and sex-matched population [1,2]. Compared with conventional sternotomy, minimally invasive mitral valve surgery (MIMVS) is associated with reduced surgical trauma, shorter hospital stays, faster recovery, and improved cosmetic outcomes, albeit with longer operative times during the learning phase [3,4,5].

Minimally invasive MV surgery may be viewed along a continuum according to the degree of dependence on thoracoscopic imaging: direct-vision, video-assisted, video-directed, and ultimately totally endoscopic surgery. The latter remains technically demanding and is performed by relatively few surgeons. In many contemporary mini-thoracotomy approaches, although the skin incision is small, a wider intercostal muscle division and partial rib spreading may still be required, particularly when direct vision is used for part of the procedure.

In contrast, robotic platforms such as the da Vinci system (Intuitive Surgical, Sunnyvale, CA, USA) facilitate a fully port-based, totally endoscopic approach. By combining high-definition three-dimensional visualization with wristed instruments, motion scaling, and tremor filtration, robotic systems overcome several technical limitations of conventional endoscopic instruments and may improve dexterity during complex intracardiac repair (Fig. 1, Ref. [6]). These features have made robotic mitral valve repair (RMVr) an increasingly adopted strategy in specialist centers.

Recent analyses have demonstrated a growing proportion of surgical mitral repair being performed robotically relative to conventional approaches [7,8,9]. The 2024 Update on National Trends and Outcomes in the Society of Thoracic Surgeons (STS) database showed that 21% of all mitral repairs were performed with a minimally invasive approach, with 9% performed robotically. Of all minimally invasive mitral repairs, 28.9% were performed robotically in 2015, whereas 40.7% were performed robotically in 2023. Regulatory barriers in Europe due to changes in Medical Device Regulations in 2021 have slowed the adoption of advanced robotic cardiac surgery systems and created an innovation bottleneck. However, Intuitive Surgical



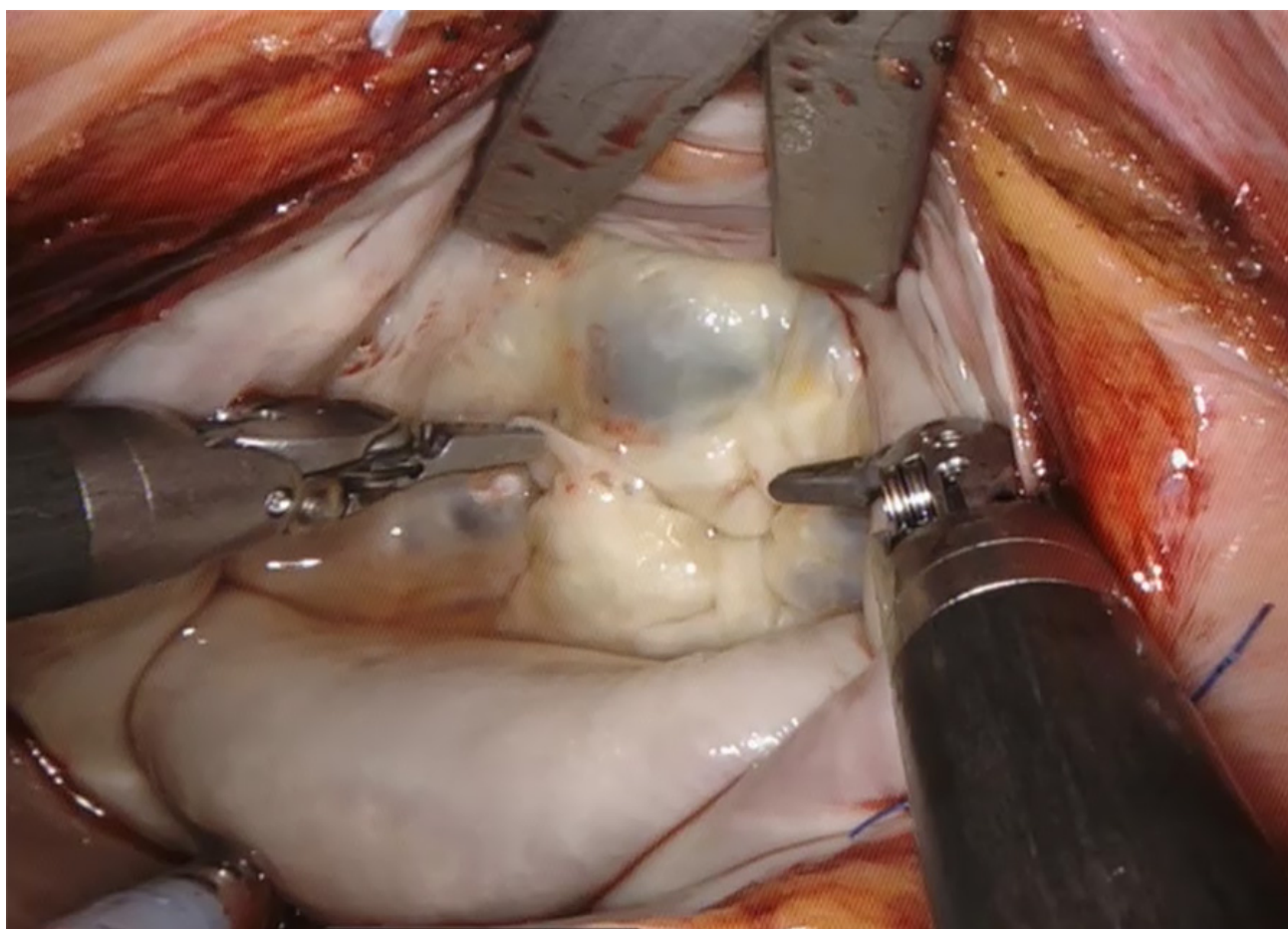


Fig. 1. The operative view with the Da Vinci (*original clinical image from our institution, from reference [6] with permission*).

are actively pursuing CE marking for intracardiac surgery for the latest generation five robotic system (da Vinci 5).

This narrative review summarizes contemporary evidence for and against robotic mitral valve surgery (RMVS), with practical implementation considerations drawn from an experienced robotic mitral programme.

Literature Search and Evidence Synthesis

To inform this narrative review, a structured targeted search of PubMed/MEDLINE was performed for English-language studies published between January 2015 and January 2026 addressing robotic mitral valve surgery in adults. Search terms included combinations of “robotic mitral valve surgery”, “robotic mitral valve repair”, “minimally invasive mitral surgery”, “mini-thoracotomy”, “sternotomy”, “mortality”, “stroke”, “durability”, “learning curve”, and “cost”.

Studies were selected on the basis of clinical relevance and methodological rigour, with priority given to comparative studies using statistical adjustment (including propensity matching or multivariable modelling), meta-analyses and national or regional database analyses. Reference lists of included articles were also screened to identify additional relevant studies. Where overlapping cohorts were

suspected, preference was given to the most recent report and/or the analysis with the most complete adjustment and follow-up.

As this was a narrative review, no formal protocol, or quantitative risk-of-bias assessment was undertaken. Findings were synthesized qualitatively, with emphasis on mortality, major morbidity, perioperative outcomes, repair durability, learning curves, program implementation, and resource utilization.

2. The Evidence For and Against Robotic Mitral Valve Surgery

A central challenge in the adoption of less invasive mitral techniques is demonstrating outcomes that are at least equivalent, and ideally superior, to those achieved with the established benchmark of median sternotomy. Randomized trials comparing operative approaches in mitral surgery are difficult to perform. Practical barriers include limited feasibility of blinding, surgeon and patient reluctance to accept sternotomy randomization in centers with mature minimally invasive or robotic programs, and loss of recruitment where patients seek treatment elsewhere to avoid allocation to a more invasive approach. Consequently, the contemporary evidence base for RMVS is derived predominantly

Table 1. Comparative evidence for robotic versus nonrobotic mitral valve surgery.

First author, year [Ref]	Study design/data source	Comparison groups	Risk adjustment	Primary endpoint	Follow-up	Mortality	Stroke	Outcomes
Paul, 2015 [11]	National Inpatient Sample 2008–2012	RMVr vs non-robotic MVr (sternotomy, minis- ternotomy, minithoracotomy)	631 propensity-matched pairs	In-hospital complications, composite outcomes	Index hospitalization	No significant difference	No significant difference	RMVr: 2 days shorter LoS; no difference in median total cost, or complications or composite outcomes.
Wang, 2018 [14]	STS adult cardiac surgery database analysis, 2011–2014	RMVr vs CSMVr	503 propensity matched pairs from 251 centres	In-hospital outcomes	3-year mortality, heart failure readmission, and mitral valve reintervention	No significant difference	No significant difference	RMVr: longer CPB and AXC times; shorter ICU hospital LoS, less transfusion & AF. No difference in 3-year mortality (HR 1.21; 95% CI 0.68 to 2.16), heart failure readmission (HR 1.42; 95% CI 0.80 to 2.52), and mitral valve reintervention (HR 0.42; 95% CI 0.15 to 1.18).
Kesävuori, 2018 [24]	Retrospective single centre	RMVr vs CSMVr	142 propensity matched pairs	In-hospital outcomes	Longest was 21 months	No significant difference	No significant difference	RMVr: longer CPB, AXC and ventilation times; no significant difference in rate of peri-operative complications. 3 patients in robotic group needed ECMO during learning curve, and 9.9% conversion to sternotomy. No difference in survival or reoperation rate.
Hawkins, 2018 [17]	Virginia Cardiac Services Quality Initiative Database, 2011–2016	RMVS vs MIMVS (n = 295 pairs) RMVS vs CSMVS (n = 314 pairs)	Propensity score matching (1:1)	Perioperative morbidity & mortality	Index hospitalization	No significant difference	No significant difference	RMVS vs MIMVS: more transfusions, AF and longer LoS. RMVS vs CSMVS: longer operative duration, higher repair rate, shorter LoS.
Coyan, 2018 [16]	Single institutional database 2013–2015	RMVr vs CSMVr	91 propensity matched pairs	Hospital costs	1-year echo follow-up in RMVS only	No significant difference	No significant difference	RMVS: longer CPB time, less ventilation, ICU and hospital LoS Total costs similar (RMVS \$27,662 vs CSMVS \$28,241; $p = 0.273$). Early direct costs higher for RMVS. Late indirect cost higher for CSMVS due to increased LoS, transfusion requirements, and readmission rates.

Table 1. Continued.

First author, year [Ref]	Study design/data source	Comparison groups	Risk adjustment	Primary endpoint	Follow-up	Mortality	Stroke	Outcomes
Seo, [25]	2019 UCLA, retrospective single centre, 2008–2016	RMVr (n = 175) vs CSMVr (n = 259)	Multivariate regression	Operative complication rates, and cost	times, Index hospitalization	No significant difference	No significant difference	RMVr: lower odds of complications (OR = 0.42, $p = 0.001$), shorter length of stay, and 11% reduction of overall direct costs ($p = 0.003$) (made up from 24% reduction in room costs ($p < 0.001$), but a 51% increase in surgery cost ($p < 0.001$)).
Takagi, [20]	2020 Meta-analysis of propensity-matched studies	RMVS vs CSMVS, n = 3764 patients, 7 propensity score matched studies	Meta-analysis using random-effects model.	Early mortality and perioperative complications	In-hospital/30-day across studies	No significant difference	No significant difference	Robotic: longer CPB/AXC times; less ICU & hospital stay, lower rates of AF & transfusion, less prolonged ventilation. Other outcomes similar.
Barac, [15]	2021 Observational comparative cohort, single institution	RMVr (n = 128) vs MIMVr (n = 249)	2:1 propensity score matched	Perioperative morbidity & mortality	5-year survival, re-operation and freedom from ≥ 2 MR	No significant difference	No significant difference	Robotic: unmatched patients were lower risk; matched patients had longer operative times, but hospital stay, morbidity and 5-year outcomes similar.
Williams, 2022 [13]	Systematic review & meta-analysis	RMVS (n = 2804 patients) vs CSMVS (n = 3537)	Mixed (adjusted + unadjusted cohorts)	Early clinical outcomes	Mostly early; limited follow-up echo data in included studies	RMVS lower mortality in unmatched and matched cohorts	No significant difference	RMVS: longer CPB/AXC; shorter ICU (26 hours) and LoS (2 days); fewer RBC transfusions. No difference in reoperation for bleeding.
Fatehi Hasanabad, 2022 [12]	Systematic review & meta-analysis, 15 studies	RMVr vs nonrobotic MVr (sternotomy, ministernotomy and minithoracotomy)	Mixed (many adjusted cohorts)	Early safety/efficacy outcomes	Mostly early; selected mid-term	No significant difference	No significant difference	RMVr: longer operative times, less AF, shorter ICU and hospital stays. No difference in 3-year and 5-year survival where available.
Husen, [10]	2023 Systematic review & meta-analysis	18 studies with 60,331 patients RMVS vs MIMVS vs CSMVS	Bayesian network meta-analysis and conventional meta-analysis (random effects model)	In-hospital outcomes	Index hospitalization	RMVS had lower mortality compared to CSMVS but not MIMVS	No significant difference	RMVS vs CSMVS: longer CPB and AXC times, lower infection rates, shorter ICU stay and hospital LoS. RMVS vs MIMVS: no difference in CPB and AXC times, or ICU and hospital LoS.

Table 1. Continued.

First author, year [Ref]	Study design/data source	Comparison groups	Risk adjustment	Primary endpoint	Follow-up	Mortality	Stroke	Outcomes
De Jesus, 2024 [22]	Systematic review/meta-analysis, 7 studies	RMVS (n = 5851 patients) vs MIMVS (n = 5972 patients)	Matched-study pooling	Comparative perioperative outcomes	Early/short-term	No significant difference	No significant difference	Robotic: longer operative times, less AF, more transfusion, shorter LoS. Otherwise, comparable safety profiles. Limited long-term durability data.
Mori, 2024 [8]	STS database analysis (degenerative MR repair), 2015–2021	RMVr vs MIMVr (n = 5540 pairs) RMVr vs CSMVr (n = 6962 pairs)	Propensity score matching	Operative outcomes and quality metrics	STS operative/30-day framework	No significant difference except in high volume centres where RMVS lower	No significant difference	Robotic: lower conversion to valve replacement, shorter LoS and fewer 30-day readmissions. Mortality & morbidity lower after 40 robotic cases and at high volume centres. No long-term data.
Sawma, 2025 [19]	Comparative cohort (older adults >65 y), Mayo Clinic, 2010–2024	RMVr vs CSMVr	Propensity score matched (189 matched pairs)	Early outcomes in older adults	Early/30-day, and 10-year survival/reintervention	No significant difference	No significant difference	Robotic: fewer blood transfusions, less AF, shorter ICU and hospital LoS. 10-year survival, recurrent MR and reintervention – no difference.
Hadaya, 2025 [26]	Outcomes + cost analysis from Nationwide Readmissions Database, 2016–2020.	RMVr vs CSMVr	Risk-adjusted	Clinical outcomes plus episode-level costs	Early outcomes; episode-based economic window	No significant difference	No significant difference	RMVr: lower rate of nonhome discharge, shorter LoS, otherwise comparable clinical outcomes. Greater risk-adjusted costs but this was volume dependent with comparable costs in highest volume tertile. Cost findings sensitive to accounting assumptions.
Noda, 2025 [21]	Retrospective claims database comparative analysis, 2019–2023, 473 hospitals in Japan	RMVr (n = 110) vs MIMVr (n = 1430)	Unmatched analysis	Clinical and cost outcomes	Index hospitalization	No significant difference	No significant difference	RMVr: higher operative day costs but comparable outcomes and total inpatient costs to minimally invasive MVr (Mini-MVr). Cost differences context-dependent.
Braasch, 2026 [7]	Retrospective analysis of Medicare data 2012–2024	RMVr vs non-robotic MVS (ster-notomy/minithoracotomy) for degenerative MR	Propensity score matching 1:2 ratio	5-year survival	Up to 5 years	No significant difference	No significant difference	RMVr: shorter LoS, lower renal failure and pacemaker, comparable survival at 1 and 5 years.

Table 1. Continued.

First author, year [Ref]	Study design/data source	Comparison groups	Risk adjustment	Primary endpoint	Follow-up	Mortality	Stroke	Outcomes
Watanabe, 2025 [18]	Japan Cardio-vascular Surgery Database, 2018–2020.	RMVr vs MIMVr Subgroup analysis of institutions doing <10 and ≥10 cases per year	577 propensity matched pairs	In-hospital outcomes	Index hospitalization	No significant difference	No significant difference	RMVr: longer CPB & AXC times, longer ICU stay, shorter hospital LoS. No difference in renal failure, prolonged ventilation, conversion to valve replacement. Higher volume institutions had better outcomes.
Eranki, 2026 [23]	Systematic review & meta-analysis	15 studies, 11,432 patients	Random effects model, weighted pooled estimates	30-day mortality	Pooled mean follow up 60.9 months (clinical) and 20.0 months (echo)	Pooled 30-day mortality 1.3%	CVA 1.4%	Mean ICU stay 1.2 days, hospital LoS 6.0 days. Survival at 10 years: 92.3%; freedom from reoperation at 5 years: 96.0%; freedom from recurrent ≥2+ MR at 5 years: 95.8%.

Abbreviations: AF, atrial fibrillation; AXC, aortic cross-clamp; CI, confidence interval; CPB, cardiopulmonary bypass; CS, conventional sternotomy; CVA, cerebrovascular accident; ECMO, extracorporeal membrane oxygenation; HR, hazard ratio; ICU, intensive care unit; LoS, length of stay; MIMVS, minimally invasive mitral valve surgery; MR, mitral regurgitation; MVr, mitral valve repair; MVS, mitral valve surgery; OR, odds ratio; R, robotic; RBC; red blood cell; STS, Society of Thoracic Surgeons.

from high-quality observational studies, including large single-center series, national database analyses, propensity-matched comparisons, and meta-analyses (Table 1, Ref. [7,8,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26]).

2.1 Early Mortality

Patients undergoing RMVS are generally a more carefully selected cohort than those treated via sternotomy. Exclusion of individuals with significant aortovascular disease (contraindicating peripheral cannulation), aortic regurgitation (AR) and mitral annular calcification (MAC) has resulted in lower-risk patients being offered robotic surgery compared to sternotomy. Consequently, unmatched comparisons have often demonstrated lower mortality among RMVS patients. As a result, unmatched comparisons frequently favour robotic surgery, whereas this apparent advantage is attenuated or lost in most adjusted analyses [8,10,11,12]. Whether higher-risk patients derive disproportionate benefit from reduced access trauma remains plausible but insufficiently tested in robust comparative datasets.

One of the largest contemporary studies was a propensity-matched comparison of MVr in the STS Adult Cardiac Surgery Database between 2015 and 2021 in which Mori et al. [8] identified 6962 pairs of RMVr vs conventional sternotomy (CS) MVr, and 5540 pairs of RMVr versus minimally invasive (MI) MVr for degenerative MR. In both comparisons, combined morbidity and mortality were not significantly different, whereas the robotic approach resulted in a shorter length of stay and fewer 30-day readmissions. Importantly, center experience influenced outcomes, with morbidity and mortality improving as cumulative robotic case volume increased, crossing the national mean at approximately 40 RMVr cases. There was a further decline in the outcome incidences towards centers exceeding 200 cases.

Similarly, in a propensity score-matched analysis of 631 pairs of patients in the National Inpatient Sample, Paul et al. [11] reported no significant differences between RMVr and non-robotic mitral valve repair in in-hospital mortality, postoperative complications, or composite in-hospital outcomes after adjustment. Across large institutional series, operative mortality after robotic mitral repair has generally remained below 1%, with several high-volume centers reporting extremely low or zero operative mortality in selected cohorts [27,28,29].

Meta-analytic evidence has generally supported comparable short-term safety. In a pooled analysis of 14 predominantly observational studies comparing 2804 robotic and 3537 conventional sternotomy mitral procedures, robotic surgery was associated with lower mortality in matched cohorts and shorter intensive care unit (ICU) and hospital stay, despite longer cardiopulmonary bypass (CPB) and aortic cross-clamp (AXC) times [13]. However, interpretation of these findings is limited by hetero-

geneity in case selection, operative technique, and residual confounding factors.

2.2 Late Survival

Longer-term comparative data also suggest broadly similar survival between robotic and non-robotic approaches after adjustment. Wang et al. [14], using the STS Adult Cardiac Surgery Database from 2011–2014, which created 503 matched pairs of RMVr and CSMVr and found no difference in 3-year mortality, heart failure readmission and mitral valve reintervention. More recently, Braasch et al. [7] reported similar risk-adjusted 5-year mortality between robotic, conventional sternotomy, and minimally invasive non-robotic mitral surgery in a retrospective Medicare analysis. In a propensity-matched comparison, Barac et al. [15] likewise found no significant difference in 5-year mortality or mitral reoperation between robotic and minimally invasive non-robotic mitral surgery.

Large expert-center series have consistently demonstrated excellent long-term outcomes after robotic repair. Mayo Clinic data demonstrated a 5-year mortality of 0.5% and a mitral reoperation rate of 2.3% in a cohort of 487 robotic repairs [30], while a later report from the same institution described 10-year survival of 93% with a mitral reoperation rate of 7.4% among 843 patients [31]. Similarly, Lio et al. [32] reported 10-year survival of $96 \pm 2\%$. Taken together, these data support excellent late survival and low reintervention rates after robotic mitral repair in experienced centers, although external generalizability remains uncertain.

2.3 Stroke, Recovery, and Other Postoperative Morbidity

Most comparative studies of RMVS versus CSMVr have demonstrated either equivalent or reduced morbidity, with shorter ICU and hospital stays, and faster return to normal activity after robotic surgery [7,11,14,16]. Wound complications are uncommon with right thoracotomy-based approaches and are rarely a distinguishing adverse event.

The principal historical concern was an increased risk of cerebrovascular accident (CVA) with less invasive mitral approaches, often attributed to retrograde perfusion. Gammie et al. [33] reported an approximately twofold increase in stroke risk with less invasive mitral techniques compared with sternotomy in an earlier STS database analysis. However, interpretation of that finding is constrained by several factors, including heterogeneous definitions of minimally invasive surgery, limited procedural standardization, low case volumes, probable learning-curve effects, retrospective design, and incomplete characterization of vascular disease and aortic pathology [34]. In that analysis, the median number of less invasive mitral cases performed per center per year was only three, suggesting that outcomes may have been strongly influenced by early adoption experience rather than mature practice.

In contrast, more contemporary series and adjusted analyses, including studies involving older patients, have not demonstrated a consistent increase in stroke risk with robotic or minimally invasive mitral surgery when compared with sternotomy [14,35,36]. These findings suggest that careful patient selection, structured imaging, and increasing technical experience may mitigate the excess neurologic risk reported in earlier datasets. Preoperative computed tomography angiography (CTA) has become an important adjunct in patient selection for minimally invasive and robotic mitral surgery. The rationale is to identify aortoiliac atherosclerosis, small-caliber femoral vessels, aneurysmal disease, tortuosity, dissection risk, and mitral annular calcification, all of which may influence cannulation strategy, cross-clamp strategy, or suitability for a robotic approach. Moodley et al. [37] demonstrated that a contrast-enhanced computed tomography (CT) of the chest, abdomen and pelvis altered the planned surgical approach in 21% of patients being evaluated for minimally invasive robotic mitral surgery, largely because of significant aortoiliac atherosclerosis or MAC. Subsequent work has supported more standardized CTA protocols, with imaging of the aorta and iliofemoral vessels used to tailor cannulation and perfusion strategy, and meta-analytic data suggest that systematic preoperative CT screening is associated with reduced stroke risk in minimally invasive mitral surgery [38].

2.4 Intensive Care and Hospital Stay

Shorter ICU and hospital stays are among the most consistent advantages reported with robotic surgery, including in comparison with mini-thoracotomy approaches [17,18,39]. Across multiple studies, hospital stay is typically reduced by 1–2 days, with shorter ventilation times and earlier ICU discharge [10,11,12,13,14,16,19,20]. This more rapid early recovery appears to translate into earlier return to normal activity and, in some studies, earlier return to work [40]. Some variability remains: for example, one report from the Japan Cardiovascular Surgery Database described a longer ICU stay in robotic patients compared with mini-thoracotomy patients, although total postoperative length of stay remained shorter [18].

2.5 Blood Transfusion and Atrial Fibrillation

Data on blood transfusion and postoperative atrial fibrillation (AF) are less consistent. Some studies have reported lower transfusion requirements and lower AF rates with robotic surgery compared with sternotomy [12,13,14,17,19,20,41], whereas others have found no significant difference [36,42]. Comparisons between robotic and minimally invasive non-robotic techniques are similarly mixed, with discordant findings across studies for both transfusion and AF [17,21,22,36]. These endpoints appear to be more sensitive to case mix, perioperative practice, and institutional workflow compared to an operative approach alone.

2.6 Repair Success and Durability up to 10 Years

Any proposed benefit of robotic surgery depends on maintaining, or ideally improving, the quality and patient experience. In this context, repair rate, recurrent MR, and reintervention are more meaningful markers of success than incision size alone.

Analysis of the STS database from 2011 to 2016 demonstrated a higher repair rate in robotic procedures than in sternotomy cases despite similar rates of degenerative pathology, although selection bias and surgeon expertise likely contributed to this finding [17]. In that study, repair techniques differed little between robotic and minimally invasive non-robotic approaches, whereas leaflet resection was more common in sternotomy cases. Large institutional robotic series, including those from high-volume centers, have reported degenerative repair rates of 98–99.5%, supporting the technical feasibility of consistent high-quality repair on the robotic platform [42,43].

Durability outcomes in expert programs have also been favorable. Murphy et al. [28] observed a decline in mitral reintervention over time in a series of 1257 patients, from 6.8% in the earliest cohort to 0.9% later in the programme. Reported 5-year freedom from reoperation of 93.8–97.7%, together with 5-year freedom from recurrent $\geq 2+$ MR of approximately 94.6–95.8%, supports the durability of robotic repair in experienced centers [23,28,30]. In patients with more complex pathology, including Barlow disease, Rowe et al. [44] reported 5-year survival free from greater than moderate MR of 92%. More recently, Chartrain et al. [45] reported a 5-year freedom from reoperation rate of 92.7% and 10-year survival of 92.8% in a registry spanning more than 1400 robotic repairs over 18 years.

Long-term data following RMVr are less mature than for sternotomy repair, but several high-volume centers now report reassuring 10-year outcomes. Roach et al. [46] reported 10-year freedom rates from greater than moderate recurrent MR or reintervention of 92% for isolated posterior leaflet prolapse and 83% for anterior or bileaflet prolapse. Chou et al. [47] reported 98% freedom from reoperation and 97.6% freedom from more than moderate MR at 10 years after robotic mitral repair, while Arghami et al. [31] reported 10-year survival of 93% and freedom from reoperation of 92.6%. Meta-analytic data similarly suggest preserved late survival, with a pooled 10-year survival of approximately 92%, although long-term echocardiographic follow-up remains heterogeneous and concentrated in expert centers [48]. These results should be interpreted in the context of careful patient selection, high-volume institutional experience, and variable completeness of long-term echocardiographic follow-up. They support the durability of robotic mitral repair in experienced programs, but they do not yet provide the same breadth of long-term evidence available for conventional sternotomy repair.

Overall, contemporary data suggest that the advantages of robotic access can be achieved without compro-

missing repair success or durability, provided procedures are performed in experienced, repair-focused programs.

2.7 Operative Times and Procedural Efficiency

Longer operative, CPB, and AXC times remain one of the most consistent disadvantages of robotic mitral surgery when compared with both sternotomy [8,12,13,14,17,20,24,41] and minimally invasive non-robotic surgery [12,15,17,18,35,39]. These differences are greatest during the learning phase and tend to diminish with institutional and surgeon experience. However, improvements in efficiency may be offset over time by increasing operative complexity as teams extend indications and undertake more challenging repairs.

Although most comparative studies report longer CPB and AXC durations with robotic surgery, not all analyses have shown a significant difference. One meta-analysis including 5851 robotic and 5972 minimally invasive non-robotic patients found no significant difference in CPB or AXC times between the two techniques, suggesting that the gap narrows substantially in mature minimally invasive programs [22].

Efforts to improve procedural efficiency in robotic mitral surgery have focused on endoscopic knot tying, which is among the more time-consuming steps. Automated titanium clip fasteners (Cor-Knot®, LSI Solutions, Victor, NY, USA) have been associated with reductions in myocardial ischemic time exceeding 20 minutes in both minimally invasive and robotic mitral surgery [49]. In addition, adoption of continuous running sutures for annuloplasty and pre-tied looped sutures for atrial closure (Fig. 2, Ref. [6]) has been associated with reductions in median cardiopulmonary bypass and aortic cross-clamp times of 32 and 19 minutes, respectively [50,51]. The broader point is that procedural efficiency improves not through technology alone, but through cumulative team familiarity, standardization, and workflow optimization.

2.8 Platform limitations and Learning Curve

A recognized limitation of robot-assisted surgery is the absence of conventional haptic feedback. Experimental and simulated-task studies suggest that force feedback can reduce tissue forces and improve task efficiency, particularly among novice robotic operators [52]. However, the apparent benefit diminishes with increasing operator experience, indicating that visual compensation and technical adaptation develop over time. The clinical impact of force-feedback systems incorporated into newer robotic platforms remains uncertain in cardiac surgery and warrants prospective evaluation.

The learning curve for robotic mitral surgery is substantial, with improvements in technical performance, post-operative complications, and intensive care and post-operative hospital stays improving for the first 400 cases

[53]. However, the greatest reduction in operation times occurs during the first 200 cases [27], and institutional proficiency may stabilize around 94 to 100 cases [54]. Many successful robotic programs have been established by teams already experienced in minimally invasive non-robotic mitral surgery, and prior experience appears to shorten the learning curve and reduce operative times, although it is not essential for adoption [55]. Familiarity with mini-thoracotomy techniques may also avoid the need for conversion to sternotomy if technical difficulties arise.

2.9 Conversion to Sternotomy and Conversion to Replacement

As institutional experience increases, conversion to sternotomy becomes less common, with reported rates falling from approximately 5–9.1% early in programme development to 0.7–1.3% in mature series [28,36,56]. Causes of conversion include bleeding, unfavourable anatomy, inadequate peripheral access, instrument conflict, and concerns regarding myocardial protection. True robotic system failure is rare but has been reported [28]. Collectively, these data reinforce that robotic outcomes are closely tied to structured adoption, case selection, and cumulative team experience.

RMVS should not be considered a repair-only strategy. Although RMVr remains the dominant application, robotic MV replacement (RMVR) is feasible in selected patients and is an important contingency when repair is not possible or proves unsatisfactory intraoperatively. If exposure is adequate and the patient remains stable, the same robotic set-up can generally be used to proceed from repair to replacement: the valve is reassessed after repair, the decision to replace is made if residual regurgitation or valve morphology is unsuitable, the native valve is excised as required, chordal preservation is performed where feasible, annular sutures are placed robotically, and the prosthesis is introduced after extending the working port and secured under three-dimensional robotic visualization with Cor-knot® (LSI Solutions, Victor, NY, USA). Suture management by the bedside assistant is critical. The threshold for conversion to a larger thoracotomy or sternotomy should remain low where exposure, bleeding, annular calcification, prosthesis delivery, prolonged cross-clamp time, or haemodynamic instability threatens safety. Conversion from robotic repair to robotic replacement should therefore be regarded as a planned contingency within a mature robotic mitral programme, not as an ad hoc rescue strategy.

2.10 Economic Context and Resource Utilization

The establishment of a robotic mitral programme requires substantial upfront capital investment, ongoing maintenance costs, and the recurring expense of limited-use instruments. In addition, longer operative times during the learning phase, which may be up to 200 cases, may reduce operating room throughput [27,53]. These factors

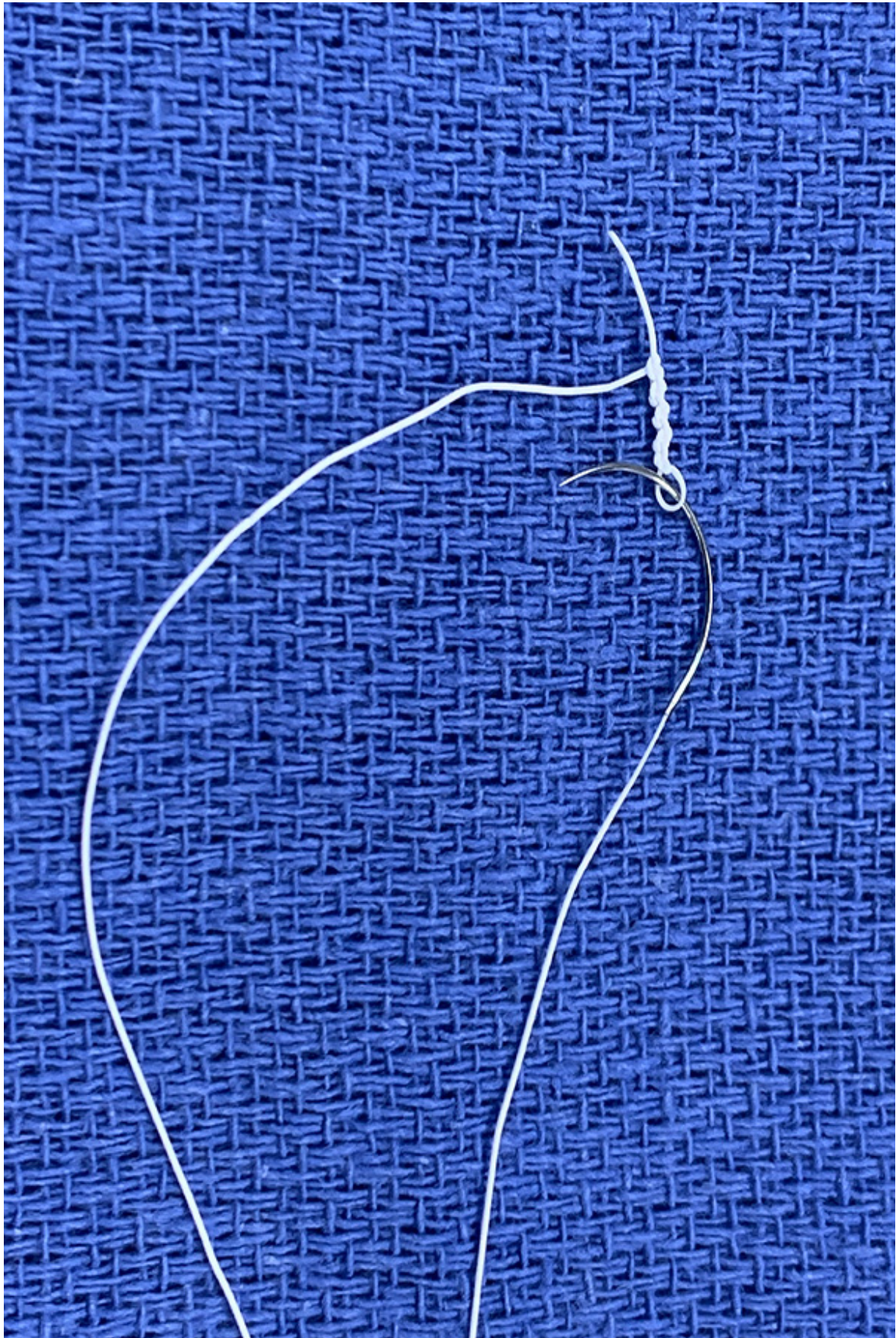


Fig. 2. Pre-knotted suture for atrial closure, made by knotting a CV4 Gore-Tex suture over a nerve hook (*original clinical image from our institution, from reference [6] with permission*).

have made cost one of the principal barriers to wider adoption.

Economic comparisons between robotic and non-robotic mitral surgery are highly dependent on analytical perspective, cost allocation, institutional volume, and local accounting practices. In a propensity-matched analysis of 631 patient pairs from the National Inpatient Sample, Paul et al. [11] reported equivalent overall costs between robotic and conventional mitral surgery, although the analysis did not include capital acquisition, maintenance, or amortization of the robotic platform. Cohan et al. [16], using a costing model that incorporated capital depreciation and instrument expenses, likewise found no significant difference in total procedural cost between robotic and sternotomy cases, with higher early direct costs in the robotic cohort offset by higher downstream indirect costs in the sternotomy cohort related to longer hospital stay, transfusion, and readmission. Noda et al. [21] similarly reported higher operative-day costs for robotic mitral surgery compared with mini-thoracotomy, but similar postoperative costs overall. In contrast, Seo et al. [25] reported lower overall direct costs for robotic compared with sternotomy repair, driven by reduced postoperative room costs from shorter hospitalizations despite more expensive operative care.

Using a broader economic model incorporating purchase, maintenance, disposables, postoperative care, and earlier return to employment, Mihaljevic et al. [40] found robotic repair to be 14–16% more expensive overall than sternotomy, partial sternotomy, or anterolateral thoracotomy, but projected cost parity at annual volumes of approximately 55–100 cases. Hadaya et al. [26] also demonstrated higher median costs for robotic versus conventional sternotomy mitral surgery overall, but found this difference narrowed substantially in the highest-volume centres, where costs were no longer significantly different. These findings support the view that volume is a major determinant of economic viability.

Interpretation of cost studies remains difficult. Results vary according to whether capital expenditure is allocated at the procedural level or treated as fixed institutional infrastructure [57], whether analyses adopt a hospital, payer, or societal perspective, and how postoperative recovery and return to work are valued. Cross-study comparison is further limited by comparator heterogeneity, case-mix differences, residual confounding, and inconsistent accounting methodology. Economic findings should therefore be interpreted as setting-specific estimates rather than universally generalizable conclusions.

Substantial resource requirements may limit accessibility in lower-volume or resource-constrained healthcare systems, where the advantages of reduced length of stay and faster recovery may not fully offset the financial and organisational costs of implementation. Accordingly, RMVS is best viewed not as a universally applicable replacement for conventional mitral surgery, but as a specialist program-

dependent approach whose value depends on case volume, institutional expertise, patient selection, and local healthcare economics.

2.11 Volume, Programme Maturity, and Sustainability

Centre volume is important not only for economic viability but also for technical proficiency, team familiarity, and programme durability. High-volume centers are better positioned to refine case selection, streamline workflow, and absorb the learning curve without sustained deterioration in outcomes. Although relatively few institutions perform more than 30 robotic mitral cases annually, established programs have shown that robotic cases can become the dominant approach within a dedicated mitral practice [28].

Experienced centers have suggested that a threshold of approximately 20 robotic mitral cases per year may represent a pragmatic minimum for maintaining team familiarity and technical proficiency [58], although this should be interpreted as an expert benchmark rather than a formal standard. Chikwe et al. [54] reported that their institutional learning curve peaked at case 94, after which risk-adjusted morbidity and mortality were consistently better than predicted. Notably, subsequent surgeons trained within that mature program achieved better-than-predicted outcomes from the outset, suggesting that institutional learning may partially mitigate the individual surgeon learning curve. By contrast, Kesävuori et al. [24] reported an increase in major complications during the early adoption phase, including extracorporeal membrane oxygenation, reoperation for bleeding, and circumflex artery occlusion. These observations reinforce that programmatic structure, mentoring, and disciplined case progression are central to safe implementation.

2.12 Robotic Mitral Valve Repair/Replacement in Severe Mitral Annular Calcification

Severe mitral annular calcification remains one of the most challenging pathoanatomic substrates for mitral valve surgery and should be regarded as a relative exclusion criterion for routine robotic mitral intervention, in all but the most experienced hands. The concern is not simply access, but the combination of impaired annular suture purchase, increased risk of paravalvular leak, atrioventricular groove disruption, circumflex coronary injury, embolization of calcium, prolonged myocardial ischaemic time, and the potential need for complex annular reconstruction. These risks are especially relevant when replacement rather than repair is required, because prosthesis seating and annular security may be compromised by bulky or circumferential calcium.

Nevertheless, severe MAC should not be considered an absolute contraindication in all patients. In expert robotic mitral programs, selected cases can be approached using a spectrum of techniques including limited decalcification, complete MAC resection, annular reconstruc-

tion, pericardial patch ventriculoplasty, and prosthetic mitral valve replacement when repair is not feasible [59]. Contemporary experience suggests that totally endoscopic robotic management of significant MAC can be performed with acceptable early outcomes in carefully selected patients, although much of the published experience comes from highly specialised centres. The available data therefore support feasibility, but not indiscriminate expansion of indications.

From a practical standpoint, the decision to perform robotic MVR in MAC should be based on detailed preoperative CT assessment of the distribution, depth, and circumferential extent of calcium; the presence of mitral stenosis; leaflet involvement; relationship to the circumflex artery; suitability for peripheral cannulation; and the anticipated need for annular reconstruction. Focal posterior MAC with preserved leaflet mobility and predictable annular reconstruction may be suitable for an experienced robotic team. In contrast, severe circumferential MAC, extensive leaflet calcification, heavy calcific mitral stenosis, small annular dimensions, hostile peripheral access, or anticipated difficulty seating a prosthesis should prompt consideration of sternotomy, alternative minimally invasive access, hybrid techniques, or transcatheter options. Thus, severe MAC is best regarded as a marker of increased technical complexity rather than an absolute contraindication; its suitability for robotic replacement depends on anatomy, institutional experience, and the availability of a clear conversion strategy.

3. Implementation Considerations

Although the technical steps of RMVr have been described in detail elsewhere, several practical principles are consistently important for the safe establishment and maturation of a robotic mitral programme. In this section, we summarize implementation considerations that may support structured adoption, efficient workflow development, and maintenance of procedural quality during program growth.

3.1 Team Training and Programme Organization

Safe implementation of robotic mitral surgery requires a deliberate, team-based approach and should be planned as carefully as acquisition of the robotic platform itself. The primary console surgeon should already be an experienced mitral operator and should complete a formal robotic training pathway before undertaking clinical cases. The initial phase of a robotic programme should not be used to learn the fundamentals of mitral valve repair or peripheral cardiopulmonary bypass management.

The wider operative team is equally important. The role of the bedside assistant—whether a second surgeon, fellow, or surgical assistant—should be clearly defined at an early stage, with team-based training implemented from program initiation. Preparation may include observation at experienced centres, wet-laboratory training, simulation,

and repeated procedural walkthroughs. Where feasible, continuity of mentorship is beneficial, particularly when the same experienced proctor can support both observational training and the initial clinical cases.

Preclinical rehearsal using simulators, synthetic valve models, or animal tissue may facilitate early familiarity with intracardiac instrument handling, port choreography, and console-to-bedside communication. Because the surgeon is physically separated from the operating table, robotic surgery places greater emphasis on communication and situational awareness than conventional open surgery. For this reason, explicit communication protocols, a shared mental model of operative flow, and a culture in which all team members feel able to raise concerns are particularly important during program establishment.

3.2 Perfusion and Myocardial Protection Planning

Our standard practice is to use internal jugular venous drainage in all patients, as this strategy makes inadequate venous return uncommon. Suboptimal drainage may compromise right-heart decompression and myocardial protection. During the learning curve, prolonged operative times necessitate systemic cooling to 28–30 °C to optimise myocardial and right lung protection. This strategy helps reduce the incidence of unilateral pulmonary oedema, an ischaemia–reperfusion injury of the right lung occurring in approximately 1% of cases and associated with a mortality rate of around 33% [60]. Additional preventive strategies include limiting the duration of single-lung ventilation, maintaining a mean arterial pressure of at least 65 mmHg during cardiopulmonary bypass, avoiding perioperative anaemia, and applying active temperature management throughout the procedure.

Single dose cardioplegia strategies, including del Nido and Custodiol[®], can simplify the conduct of RMVS by reducing interruptions for repeated cardioplegia delivery and by allowing the surgeon to maintain focus within a highly choreographed endoscopic workflow. However, this advantage should be balanced against an important technical pitfall: repeated pressurized saline testing of the mitral repair (e.g., with battery-powered saline irrigation devices that are not pressure-limited) can dilute or wash out cardioplegic solution from the left ventricle and potentially compromise myocardial protection. This is particularly relevant during the learning phase, when cross-clamp times are longer, repair assessment may be repeated several times, and the interval between the initial cardioplegia dose and aortic unclamping may be extended.

For this reason, single-dose cardioplegia should not be interpreted as “set-and-forget” myocardial protection. Surgeons should minimise unnecessary repeated pressurization of the left ventricle, perform saline testing in a controlled and purposeful manner, and maintain active communication with the anaesthetic and perfusion teams regarding cross-clamp duration, electrical activity, and ven-



Fig. 3. The Lateral Endoscopic Approach for Robotics (LEAR) Technique (*original clinical image from our institution, from reference [6] with permission*). A, access port; E, endoscope port; L, left arm port; LA, left atrial retractor port; R, right arm port.

tricular distension. If repeated saline testing has been required, electrical activity returns, or the cross-clamp interval is prolonged, additional cardioplegia should be administered. Some programs deliberately re-dose cardioplegia during or after repair testing, particularly when repair complexity or prolonged ischaemic time is anticipated.

Thus, while del Nido or Custodiol may be useful for robotic mitral programmes, they should be embedded within a structured myocardial protection protocol. During early program development, the threshold for redosing should be conservative, because prolonged cross-clamp times and repeated repair testing are predictable features of the learning curve. The convenience of a single-dose strategy should never supersede the fundamental objective of reliable myocardial protection. In robotic mitral repair, repeated saline testing should be treated as a myocardial protection event, not merely as a repair-assessment manoeuvre.

3.3 Aortic Occlusion Strategy

Aortic occlusion in robotic mitral surgery should now be considered less as a binary technical choice between

endoaortic balloon occlusion and transthoracic clamping, and more as a programme-level decision shaped by patient anatomy, imaging, institutional experience, cost, and team maturity. Earlier descriptions of robotic mitral surgery often emphasised the technical appeal of the endoballoon in enabling a fully port-based operation (Fig. 3, Ref. [6]) [28]. Contemporary practice is more selective. Endoaortic balloon occlusion can facilitate a totally endoscopic lateral approach, but it introduces a distinct learning curve involving balloon position, migration, root pressure, cardioplegia delivery, cerebral perfusion, and suitability of the aortoiliac axis for retrograde perfusion. For this reason, its use should be supported by preoperative CT assessment, transoesophageal echo (TOE) expertise, perfusion familiarity, and a clear protocol for repositioning, conversion to another occlusion strategy, or sternotomy.

Technical refinements such as filling the IntraClude balloon with albumin–indocyanine green solution to allow fluorescence-guided confirmation of balloon position illustrate how robotic programmes have moved from feasibility toward reliability (Fig. 4, Ref. [6]) [61]. However, such

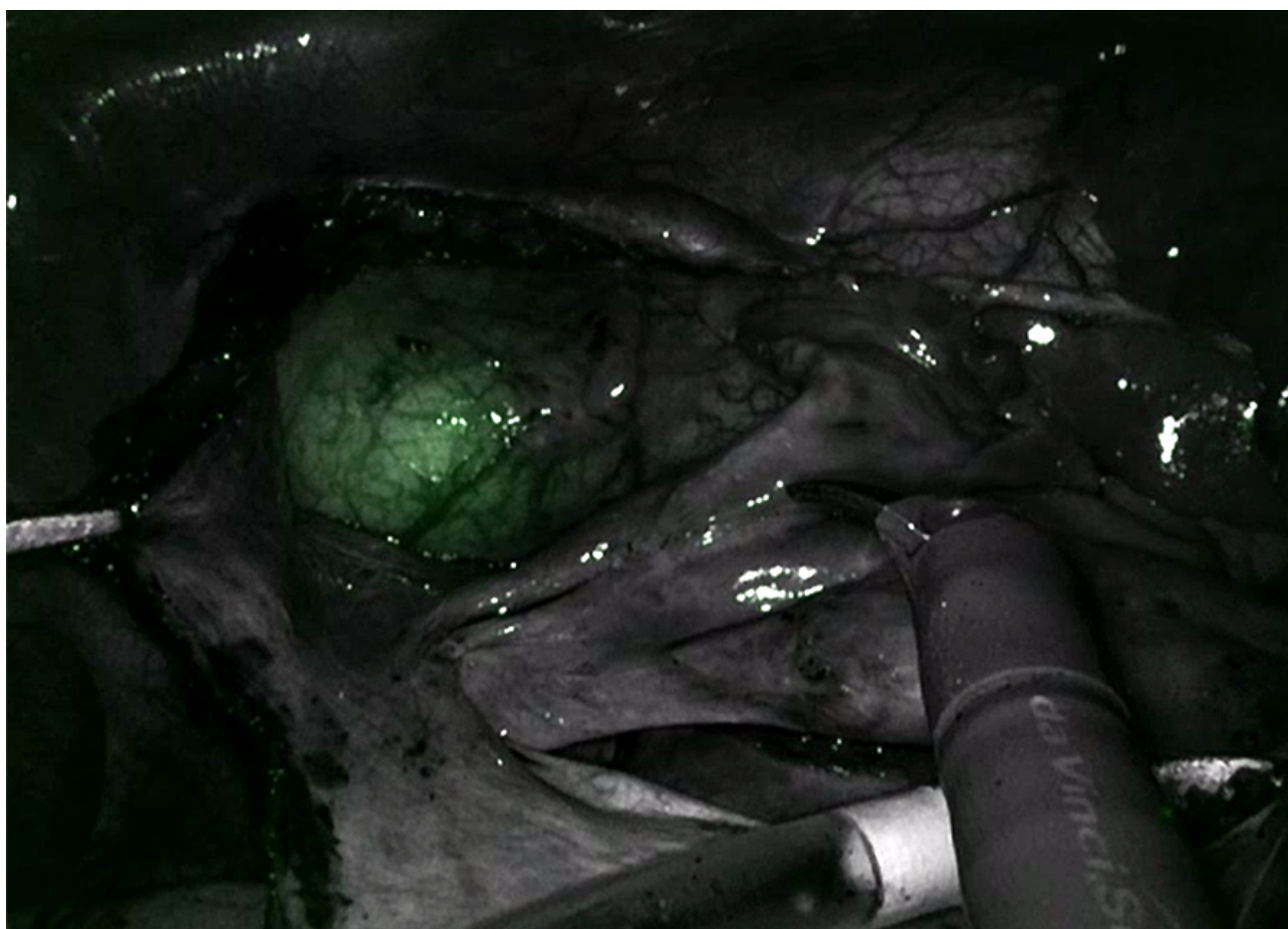


Fig. 4. Indocyanine green fluorescing in the IntraClude in the mid ascending aorta (*original clinical image from our institution, from reference [6] with permission*).

adjuncts should be regarded as additional safeguards rather than replacements for conventional monitoring. The cost of single-use endoaortic occlusion systems also remains relevant, particularly in socialized healthcare systems with constrained resources where robotic surgery must demonstrate value as well as technical sophistication.

External transthoracic clamping remains a dependable and often more economical alternative, particularly for teams transitioning from mini-thoracotomy mitral surgery. It avoids balloon migration and provides familiar aortic control, but it also requires its own standardised workflow and may create instrument crowding or ergonomic conflict. The safest occlusion strategy is therefore not necessarily the most technologically advanced or the most “totally endoscopic”, but the one that best matches the patient’s anatomy and the team’s reproducible expertise.

3.4 Case Selection and Phased Adoption

Careful case selection is fundamental to safe program development. The choice of operative approach—robotic, mini-thoracotomy, or sternotomy—should be guided by three principles: patient safety, quality and durability of valve reconstruction, and delivery of these objectives

through the least invasive approach appropriate to the individual patient.

During the earliest phase of program adoption, ideal candidates are those with favourable peripheral access, uncomplicated thoracic anatomy, and isolated degenerative pathology of the posterior leaflet amenable to straight-forward repair. Early selection should remain intentionally conservative, with indications broadened incrementally as team consistency, procedural efficiency, and confidence improve. This phased strategy helps minimize avoidable conversion, reduces cognitive load during the learning phase, and allows the programme to mature without simultaneously expanding technical complexity.

Preoperative cross-sectional imaging is particularly valuable in robotic mitral surgery. Assessment of the aortoiliac axis, peripheral vessels, atherosclerotic burden, and thoracic anatomy can inform cannulation strategy, aortic occlusion planning, and overall suitability for a robotic approach. In addition to improving technical planning, structured preoperative imaging may help reduce neurological risk through more informed selection of arterial perfusion strategy.

Many centers begin with relatively conservative exclusion criteria, including significant aortoiliac disease, severe mitral annular calcification, relevant aortic regurgitation, reoperative status, severe ventricular dysfunction, marked pulmonary hypertension, or limited peripheral access [27,62]. However, with increasing program experience, many of these factors become relative rather than absolute contraindications. As technical expertise develops, alternative cannulation strategies, broader anatomical indications, and selected reoperative cases may be incorporated safely. Even so, expansion of indications should be deliberate and data-driven rather than driven by enthusiasm alone.

3.5 Workflow Standardization and Programme Maturation

Beyond individual technical skill, successful robotic mitral surgery depends on standardization of workflow. This includes consistent port placement, reproducible cannulation and occlusion strategies, clearly defined team roles, and structured responses to predictable intraoperative challenges. The transition from an early robotic programme to a mature one is often marked less by major changes in operative technique than by cumulative gains in efficiency, communication, and anticipation.

Prospective audit of procedural times, conversions, complications, transfusion requirements, reinterventions, and repair durability is therefore essential. Early identification of recurrent workflow delays or adverse-event patterns can guide targeted process improvement, case selection refinement, and additional team training. In this context, robotic programme development should be regarded as a continuous quality-improvement process rather than a one-time technical adoption.

A stepwise approach to programme expansion is advisable. Initial focus should be on safe reproducibility in lower-complexity cases, followed by gradual extension to more anatomically complex repairs and higher-risk patients as outcomes stabilize. This staged progression allows the programme to develop technical depth while protecting early results and preserving team confidence.

3.6 Practical Perspectives

The principal determinant of a successful robotic mitral program is not the robotic platform alone, but the interaction between surgical expertise, team structure, patient selection, and disciplined implementation. Centres that achieve strong outcomes typically combine formal training, conservative early indications, standardized workflows, and continuous performance review. Conversely, attempting to expand indications too early, adopt multiple new technical components simultaneously, or rely on technology in the absence of programme structure may increase complications and undermine sustainability.

Robotic mitral surgery is therefore best introduced as a structured programme rather than an isolated operative technique. When implemented in this way, it can support

safe adoption, progressive efficiency gains, and preservation of high-quality reconstructive outcomes.

3.7 Limitations

Several limitations should be acknowledged. No randomized trials were identified, and the contemporary evidence base is derived predominantly from observational studies, with inherent risks of residual confounding, selection bias, and center-volume effects. Patients undergoing robotic surgery are often more selectively chosen than those treated through sternotomy, which may influence both perioperative and longer-term comparisons despite statistical adjustment.

Comparator groups are also heterogeneous, particularly where minimally invasive non-robotic cohorts include a range of thoracotomy-based techniques with differing operative strategies and learning curves. Much of the strongest evidence originates from high-volume expert centers, which may limit external generalizability to lower-volume programs or those in earlier phases of adoption.

Economic analyses are especially sensitive to differences in analytic perspective, treatment of capital expenditure, institutional volume, and local accounting methodology. As a result, direct comparisons of cost-effectiveness across studies should be interpreted cautiously. These factors limit cross-study comparability and should temper broad conclusions regarding superiority, generalizability, or economic advantage.

4. Conclusions

RMVS has moved beyond proof of concept and now represents a mature, minimally invasive platform for mitral intervention in appropriately selected centers. Across contemporary series from experienced programs, robotic approaches have been associated with high repair rates, low mortality and morbidity, shorter hospital stays, and faster functional recovery when compared with conventional sternotomy pathways.

Robotic mitral surgery is increasingly judged alongside rapidly advancing transcatheter mitral therapies. Robotic surgery must offer more than a small incision; it must deliver a durable repair at low operative risk, and rapid recovery. Newer robotic generations (e.g., da Vinci 5, Intuitive Surgical) will improve visualization, ergonomics, fluorescence integration and digital workflow analysis, and facilitate continuous improvement. The principal challenges remain the complexity of program establishment, the length of the learning curve, and the dependence of outcomes and cost-efficiency on institutional volume, team experience, and case selection. These factors are predictable and potentially modifiable through structured team training, standardized workflows, careful patient selection, and prospective quality oversight.

The key message is not that robotic surgery should replace all mitral surgery, but that it should be considered

a strategic extension of modern mitral practice where resources, expertise, and case volume are sufficient. Within a dedicated, protocol-driven programme, robotic surgery may expand access to totally endoscopic repair while improving patient experience and maintaining high-quality reconstructive outcomes.

Abbreviations

AF, atrial fibrillation; AXC, aortic cross-clamp; CPB, cardiopulmonary bypass; CS, conventional sternotomy; CT, computed tomography; CVA, cerebrovascular accident; ICU, intensive care unit; LEAR, lateral endoscopic approach for robotics; LoS, length of stay; MI, minimally invasive; MR, mitral regurgitation; MVR, mitral valve repair; MVS, mitral valve surgery; RBC, red blood cell; R, robotic; STS, Society of Thoracic Surgeons.

Author Contributions

PM, EC, FB, and JM made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; PM, EC, FB, and JM drafted the manuscript; all authors read and approved the final manuscript; all authors agree to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

Not applicable.

Acknowledgment

Not applicable.

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflicts of interest.

Declaration of AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work the authors used ChatGPT 5.2 in order to edit the text. After using this tool, the authors reviewed the content as needed and take full responsibility for the content of the publication.

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