

Hospital Costs and Procedural Learning Curves of Robotic Mitral Valve Surgery: A Systematic Review and Meta-Analysis

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Abstract

Background

Robotic-assisted mitral valve surgery offers a less invasive alternative to traditional open sternotomy, with potential benefits including faster recovery and reduced morbidity. However, the higher upfront expenses have slowed its broader acceptance. This study aimed to synthesize existing evidence comparing robotic and conventional mitral valve procedures regarding overall hospital expenses, intraoperative and post-procedure costs, as well as learning trajectory parameters including aortic cross-clamp and cardiopulmonary bypass durations.

Methods

A systematic search of PubMed, Scopus, Web of Science, and the Cochrane Library was conducted up to May 2026 to identify studies reporting cost or learning curve outcomes. A random-effects model with restricted maximum likelihood estimation was used in R software for all pooled analyses.

Results

Seventeen studies met inclusion criteria. Total hospital costs from five studies (91,541 participants) showed no significant difference between approaches (MD + 1,620 USD; $p = 0.423$) with high heterogeneity ($I^2 = 99.3\%$). Leave-one-out analysis excluding one large US database study demonstrated significantly lower total costs for robotic surgery ($p < 0.001$) with no heterogeneity. Robotic procedures had higher intraoperative costs (MD + 2,144 USD; $p < 0.001$) but lower postoperative costs (MD -556 USD; $p < 0.001$). The learning phase trended toward longer cross-clamp and bypass times versus proficiency, with no differences between proficiency and mastery phases.

Conclusions

Robotic mitral valve surgery entails higher intraoperative costs but yields significantly lower postoperative expenses relative to conventional approaches. The net financial impact depends heavily on the costing methodology employed, with activity-based costing studies suggesting cost equivalence or savings. The learning curve data remains limited to draw definitive conclusions highlighting the need for future studies with standardized definitions.

Introduction

Mitral valve disease is among the most prevalent valvular heart disorders, with surgical intervention remaining the standard of care for patients with severe primary mitral regurgitation (1, 2). For patients with mitral valve disease who need valve replacement and are not candidates for repair, treatment options include conventional sternotomy and various minimally invasive approaches. Over the past three decades, the field has shifted away from median sternotomy toward less invasive techniques such as mini-thoracotomy and robotic procedures (3, 4). Since the first complete robotic mitral valve repair using the da Vinci system in 1998, the approach has become well established. According to the Society of Thoracic Surgeons database, robotic mitral valve repairs increased by 30% between 2015 and 2021, while sternotomy-based repairs declined correspondingly (3, 5, 6).

Accumulating evidence from large institutional series and national databases has demonstrated that robotic mitral valve surgery achieves comparable mortality, high repair rates exceeding 98–99%, and favorable short- and long-term durability when compared with conventional sternotomy and thoracotomy approaches (7, 8). Propensity-matched analyses stated lower conversion to valve replacement, shorter hospital length of stay, fewer 30-day readmissions, and reduced morbidity (6, 9).

Two interrelated concerns have limited broader adoption of robotic mitral valve surgery despite its favorable clinical outcomes: cost and the procedural learning curve (10, 11). The robotic platform requires substantial capital investment, ongoing maintenance, and more expensive disposable instruments than conventional approaches (11, 12). Whether these higher upfront costs are offset by downstream savings, through shorter ICU and hospital stays, fewer transfusions, lower readmission rates, and earlier return to work, remains debated (11, 13). Some institutional analyses have shown cost neutrality or even savings once procedural volume increases and system efficiencies are achieved, while others report persistent incremental costs, particularly in lower-volume settings (9, 11, 12, 14). Comparisons across studies are difficult due to differences in cost accounting methods, healthcare reimbursement structures across countries, and whether indirect costs like capital depreciation or productivity losses are included (11, 15).

The learning curve is a second critical barrier because it directly affects operative efficiency, clinical outcomes, and ultimately cost (10). Estimates of the number of cases needed to achieve proficiency vary widely: roughly 30 cases to stabilize cardiopulmonary bypass and cross-clamp times, 40 cases to reach national averages for mortality and morbidity, and up to 93 cases to achieve operative mastery and expand to more complex patients (16, 17). Cumulative sum analyses from experienced programs have shown progressive reductions in operative times, complication rates, and resource use as institutional and individual surgeon experience accumulates (13, 18). To date, no systematic review or meta-analysis has comprehensively synthesized the available evidence on both the costs and learning curves of robotic mitral valve surgery. This study consolidates existing data to provide a framework for understanding the economic and educational dimensions of adopting this technology.

Methods

Data sources and search strategy

This review followed PRISMA 2020 statement and Cochrane handbook recommendations for systematic reviews (19, 20). Four electronic databases, PubMed, Scopus, Web of Science, and the Cochrane Library, were searched from their inception dates through May 14, 2026. No restrictions were placed on language or publication type during the search phase. The search strategy combined three thematic blocks using Boolean operators. The first block captured robotic surgery concepts using terms such as "robotic mitral valve surgery," "da Vinci mitral," "robotic mitral valve replacement". The second block captured comparator concepts including "sternotomy," "conventional mitral valve surgery," "open mitral valve surgery". The third block captured outcome concepts including "cost," "healthcare cost," "hospital cost," "learning curve," "proficiency," and "operative time." The complete search strings for each database are provided in Supplementary Table S1. Two reviewers independently performed title and abstract screening, followed by full-text assessment of potentially eligible articles. Disagreements at either stage were resolved through discussion or by consulting a third reviewer.

Eligibility criteria

Studies were considered eligible if they met all of the following criteria using the PICO framework. The population consisted of adult patients undergoing isolated mitral valve repair or replacement for any underlying etiology. The intervention was robotic-assisted mitral valve surgery performed using any generation of the da Vinci surgical system. The comparator was conventional mitral valve surgery performed via median sternotomy or non-robotic minimally invasive approaches including mini-thoracotomy. Outcomes of interest included at least one of the following: total hospital costs, operative costs, postoperative costs, or learning curve parameters defined as cross-clamp time or cardiopulmonary bypass time across clearly defined learning phases. The study design was limited to comparative cohort studies or learning curve analyses with explicitly defined phase transitions. Case reports, case series lacking comparators, editorials, and conference abstracts with insufficient data for extraction were excluded.

Data extraction

Two reviewers independently extracted data onto a purpose-built Excel spreadsheet organized into three domains. Study-level characteristics included study design, country, total sample size, population descriptors, inclusion and exclusion criteria, follow-up duration, and author-reported key conclusions. Baseline participant data included number of participants per arm, mean age, sex distribution, comorbidities, and cardiac risk profile. Outcome data included raw numbers of events or summary statistics for each endpoint of interest, with particular attention to cost values expressed in US dollars and learning curve phase definitions. For cost outcomes, data were extracted as mean values with standard deviations whenever available. For learning curve outcomes, cross-clamp and cardiopulmonary bypass times were extracted for each defined phase. Definitions of extracted outcomes are presented in Supplementary Tables S2-6. Discrepancies were resolved by discussion or by consulting a third reviewer.

Risk of bias assessment

The Newcastle-Ottawa Scale was used by two independent authors to evaluate each included non-randomized study across three domains: selection of cohorts, comparability of cohorts, and ascertainment of outcomes (21). A third reviewer arbitrated any disagreements.

Statistical synthesis and heterogeneity assessment

All analyses were conducted in R (Version 4.6.0, R Core Team) using the meta package. Using a random-effects model with the constrained maximum-likelihood estimator for between-study variance (τ^2) and the inverse-variance (IV) approach, we performed a pairwise meta-analysis. Mean differences (MDs) were employed as effect measures, and all outcomes were continuous. A two-sided p-value of less than 0.05 was considered statistically significant, and all estimates were accompanied by the matching 95% confidence intervals (CIs). The I² statistic and the Cochran's Q test were used to measure heterogeneity; I² $\geq$ 50% or a Cochran's Q p-value $<$ 0.1 were deemed indicative of significant heterogeneity. To determine whether a single study has a disproportionate impact on the pooled estimate, leave-one-out (LOO) sensitivity analysis was performed. Due to the small number of included papers, publication bias was not formally evaluated.

Results

Search results and study characteristics

The combined database search yielded 455 records. After duplicate removal, 283 unique citations proceeded to title and abstract screening, of which 23 advanced to full-text evaluation. Following full-text assessment, six additional records were excluded: one for wrong population, three for wrong intervention or comparator, and two for wrong outcome. Ultimately, 17 studies met all eligibility criteria and were included in the final analysis as in Fig. 1. Of these, ten studies reported cost outcomes (11–15, 22–26) and seven studies reported learning curve outcomes (16, 17, 27–31).

Seventeen studies published between 2005 and 2026 met the inclusion criteria. The evidence base spanned nine countries across three continents, with nine studies from the United States, two from Turkey, and one each from Taiwan, Germany, Japan, Australia, Spain, the Netherlands, and Italy. Sample sizes varied considerably, ranging from 32 patients in the smallest study (Yaffee et al., 2014) to over 50,000 participants in the largest database analyses (Paul et al., 2015). Four studies used propensity score matching to balance baseline characteristics, one applied inverse probability of treatment weighting, and the remainder used multivariable regression or descriptive comparisons. The specific procedures examined included mitral valve repair and replacement across degenerative, rheumatic, and other etiologies. Detailed study characteristics are presented in Table 1, and baseline patient characteristics are summarized in Table 2.

Table 1
Study Summary

Study ID	Study design	Country	Total sample size, no.	Population	Inclusion criteria	Intervention	Control	Ma
Chien et al. 2025	Retrospective cohort, IPTW	Taiwan	5,736	Patients undergoing isolated mitral valve replacement (2016–2021)	Diagnosis of mitral valve disease (ICD-10 I34) in ≥ 2 outpatient visits or ≥ 1 hospitalization within 1 year; AND surgical mitral valve replacement (ICD-10 02RG); Excluded: concurrent aortic valve replacement or CABG	Robotic-assisted MVR (RAMVR) (ICD-10 02RG4 + procedure codes 26001, 26006, 26003)	Conventional sternotomy MVR (CSMVR) (ICD-10 02RG0)	RA sig ter sh vs sta low dia 1-y co:
Chikwe et al. 2025	Retrospective cohort, CUSUM	USA	1,411	Patients undergoing robotic mitral surgery for any etiology (2005–2023)	All patients undergoing robotic mitral valve surgery (repair or replacement) for any etiology at a single institution; Excluded: surgeon with too few cases to analyze	Robotic mitral valve surgery	None (learning curve analysis only)	Ins pe: Su bel ou' De 99.
Coyan et al. 2018	Retrospective, propensity-matched	USA	182 (91 matched pairs)	Patients undergoing isolated mitral valve repair or replacement (2013–2015)	First-time mitral valve repair or replacement by experienced surgeons; Excluded: severe aortoiliac occlusive disease, concomitant procedures other than tricuspid repair/ASD closure/ablation, reoperation, emergent/salvage surgery	Robotic MV repair/replacement (RMVR) via mini-thoracotomy with da Vinci system	Sternotomy MV repair/replacement (SMVR)	To: bel wa ecl rec yea
Franke et al. 2022	Retrospective cohort	Germany	182	Patients undergoing robotic MVR (2019–2021)	Consecutive patients undergoing robotic-assisted MVR; Excluded: severe obesity, reoperations, severe diaphragmatic elevation, severe mitral annular calcification, high probability of replacement, ascending aneurysm > 40 mm	Robotic MVR (isolated or complex with tricuspid repair/Cox-Maze/PVI/LAA closure)	Mini-thoracotomy mitral surgery (MIMS) for cost comparison	Lei: 25' tim shi co: du
Giroletti et al. 2023	Retrospective cohort	Italy	149	Patients undergoing RAMVS (2019–2023)	All patients undergoing robotic-assisted mitral valve surgery (repair or replacement) for any etiology (regurgitation or	Robotic MV repair/replacement	None (learning curve analysis)	Lei: CP ski no: Sta lea

Abbreviations: AF, atrial fibrillation; ASD, atrial septal defect; CABG, coronary artery bypass grafting; CPB, cardiopulmonary bypass; CSMVR, conventional sternotomy mitral valve replacement; CUSUM, cumulative sum analysis; DPC, diagnostic procedure combination; HR, hazard ratio; ICD-9/ICD-10, International Classification of Disease Revision; ICU, intensive care unit; IPTW, inverse probability of treatment weighting; IQR, interquartile range; LAA, left atrial appendage; LOS, length of stay; MVR, mitral valve surgery; MIMS, minimally invasive mitral surgery (mini-thoracotomy); MR, mitral regurgitation; MV, mitral valve; MVR, mitral valve replacement; N Sample; NYHA, New York Heart Association functional classification; OR, odds ratio; PFO, patent foramen ovale; PVI, pulmonary vein isolation; RAMVR, robotic mitral valve replacement; RAMVS, robotic-assisted mitral valve surgery; RMVR, robotic mitral valve repair/replacement; SD, standard deviation; SMVR, sternotomy mitral valve repair/replacement; TERMR, totally endoscopic robotic mitral valve repair.*

Study ID	Study design	Country	Total sample size, no.	Population	Inclusion criteria	Intervention	Control	Me
					stenosis); Excluded: coronary artery disease requiring intervention			
Güllü et al. 2021	Retrospective cohort, CUSUM	Turkey	60	Patients undergoing robotic-assisted isolated MV repair (2010–2019)	Consecutive patients undergoing robotic-assisted isolated mitral valve repair; Excluded: symptomatic coronary artery disease, aortic valve insufficiency, pectus excavatum, intensive pleural adhesions	Robotic MV repair	None (learning curve analysis)	Lei at : tirn to fro mc
Hadaya et al. 2025	Retrospective cohort	USA	40,738	Adults undergoing elective MV repair for mitral insufficiency (2016–2020)	Adults undergoing elective mitral valve repair; Excluded: rheumatic heart disease, mitral stenosis, concomitant CABG or non-mitral valve surgery, missing data	Robotic-assisted MV repair	Conventional MV repair (sternotomy or thoracotomy, non-robotic)	Co ou str hai (46 bu vol co:
Kadiroğulları et al. 2026	Retrospective cohort, CUSUM	Turkey	233	Patients undergoing robotic MVR (2013–2024)	Consecutive patients undergoing robotic mitral valve replacement; Excluded: moderate-severe aortic insufficiency, significant aorto-iliac disease, femoral artery <7mm, redo cardiac surgery	Robotic MVR	None (learning curve analysis)	Th lea prc ma ca: op
Kam et al. 2010	Retrospective cohort	Australia	147	Patients undergoing isolated MVR for degenerative disease (2005–2008)	Age ≥ 18 years; elective, isolated mitral valve repair for degenerative mitral valve disease; Excluded: coronary lesions requiring bypass	Robotic MVR via da Vinci system	Conventional MVR (sternotomy)	No tot rob grc ho: op
Mihaljevic et al. 2014	Retrospective, propensity-matched	USA	1,290	Patients with posterior leaflet prolapse undergoing MV repair (2006–2010)	First-time isolated posterior leaflet repair for degenerative mitral valve disease; Excluded: concomitant procedures except PFO closure or pulmonary vein isolation	Robotic-assisted MV repair	Complete sternotomy, Partial sternotomy, Anterolateral thoracotomy	Ro tot fas vs nei hig 55

Abbreviations: AF, atrial fibrillation; ASD, atrial septal defect; CABG, coronary artery bypass grafting; CPB, cardiopulmonary bypass; CSMVR, conventional sternotomy mitral valve replacement; CUSUM, cumulative sum analysis; DPC, diagnostic procedure combination; HR, hazard ratio; ICD-9/ICD-10, International Classification of Diseases, 9th/10th Revision; ICU, intensive care unit; IPTW, inverse probability of treatment weighting; IQR, interquartile range; LAA, left atrial appendage; LOS, length of stay; MI, myocardial infarction; MIMMS, minimally invasive mitral surgery (mini-thoracotomy); MR, mitral regurgitation; MV, mitral valve; MVR, mitral valve replacement; N, number of patients; NYHA, New York Heart Association functional classification; OR, odds ratio; PFO, patent foramen ovale; PVI, pulmonary vein isolation; RAMVR, robotic mitral valve replacement; RAMVS, robotic-assisted mitral valve surgery; RMVR, robotic mitral valve repair/replacement; SD, standard deviation; SMVR, sternotomy mitral valve replacement; TERMR, totally endoscopic robotic mitral valve repair.*

Study ID	Study design	Country	Total sample size, no.	Population	Inclusion criteria	Intervention	Control	Me
Morgan et al. 2005	Retrospective cohort	USA	40	Patients undergoing ASD closure or MV repair	Consecutive patients at start of robotics program undergoing ASD closure or mitral valve repair	Robotic ASD closure / MV repair (da Vinci system)	Sternotomy ASD closure / MV repair	Ro sig ho: an co: mc
Noda et al. 2025	Retrospective cohort	Japan	1,540	Patients undergoing MVR under general anesthesia (2019–2023)	Patients undergoing mitral valve repair under general anesthesia in DPC-participating hospitals; identified using procedure code master (L008)	Robotic-assisted MV repair	Minimally invasive MVR (Mini-MVR via right mini-thoracotomy)	Op sig rot co: ou: coi
Paul et al. 2015	Retrospective, propensity-matched	USA	50,408	Patients undergoing isolated MV repair (2008–2012)	Elective isolated mitral valve repair (ICD-9 35.12); Excluded: concomitant procedures; Age ≥ 18 years	Robotic-assisted MV repair (ICD-9 17.4x)	Non-robotic MV repair (sternotomy or minimally invasive without robotics)	No or: ha: vs dif
Sandoval et al. 2024	Prospective, CUSUM	Spain/Netherlands	124	Patients undergoing robotic MV repair for leaflet prolapse (2019–2023)	First consecutive patients undergoing robotic-assisted mitral valve repair for severe degenerative leaflet prolapse; Excluded: concomitant procedures other than AF ablation or PFO closure	Robotic MV repair	None (comparison of centers with/without prior MIMVS experience)	Pri sh: (50 ba: (11 cla mi
Seo et al. 2019	Retrospective cohort	USA	434	Patients undergoing isolated MV repair (2008–2016)	Isolated mitral valve repair (robotic or open); Excluded: concomitant procedures, previous cardiac operations	Robotic MV repair (single surgeon beyond learning curve)	Open MV repair (sternotomy)	Ro lov co: sh: lov de: co:
Suri et al. 2013	Retrospective, propensity-matched	USA	370 (185 matched pairs)	Patients undergoing isolated MV repair for leaflet prolapse (2007–2011)	Primary mitral valve repair for leaflet prolapse; Excluded: congenital, rheumatic, or ischemic disease; active endocarditis; peripheral vascular disease; extensive coronary disease; concomitant procedures except ASD/PFO closure or maze	Robotic MV repair	Conventional open MV repair (sternotomy)	Be inn hig (34 Aft sin (30 Ro sh: LO
Yaffee et al. 2014	Retrospective cohort	USA	32	Patients undergoing TERMR (first programmatic year)	Consecutive patients undergoing totally endoscopic robotic mitral valve repair after structured team training; Excluded:	Totally endoscopic robotic MV repair (TERMR) with da Vinci Si system	None (learning curve analysis after structured pretraining)	Aft cla lea on tir pei mc

Abbreviations: AF, atrial fibrillation; ASD, atrial septal defect; CABG, coronary artery bypass grafting; CPB, cardiopulmonary bypass; CSMVR, conventional sternotomy mitral valve replacement; CUSUM, cumulative sum analysis; DPC, diagnostic procedure combination; HR, hazard ratio; ICD-9/ICD-10, International Classification of Diseases, 9th/10th Revision; ICU, intensive care unit; IPTW, inverse probability of treatment weighting; IQR, interquartile range; LAA, left atrial appendage; LOS, length of stay; MIMVS, minimally invasive mitral valve surgery; MIMVS, minimally invasive mitral surgery (mini-thoracotomy); MR, mitral regurgitation; MV, mitral valve; MVR, mitral valve replacement; N Sample; NYHA, New York Heart Association functional classification; OR, odds ratio; PFO, patent foramen ovale; PVI, pulmonary vein isolation; RAMVR, robotic-assisted mitral valve repair/replacement; RMVR, robotic mitral valve repair/replacement; SD, standard deviation; SMVR, sternotomy mitral valve repair/replacement; TERMR, totally endoscopic robotic mitral valve repair.*

Study ID	Study design	Country	Total sample size, no.	Population	Inclusion criteria	Intervention	Control	Me
					previous cardiac surgery, severe pectus deformities, severe mitral annular calcification, severe aortic atherosclerotic disease			
Abbreviations: AF, atrial fibrillation; ASD, atrial septal defect; CABG, coronary artery bypass grafting; CPB, cardiopulmonary bypass; CSMVR, conventional ste replacement; CUSUM, cumulative sum analysis; DPC, diagnostic procedure combination; HR, hazard ratio; ICD-9/ICD-10, International Classification of Disea Revision; ICU, intensive care unit; IPTW, inverse probability of treatment weighting; IQR, interquartile range; LAA, left atrial appendage; LOS, length of stay; MI mitral valve surgery; MIMS, minimally invasive mitral surgery (mini-thoracotomy); MR, mitral regurgitation; MV, mitral valve; MVR, mitral valve replacement; N Sample; NYHA, New York Heart Association functional classification; OR, odds ratio; PFO, patent foramen ovale; PVI, pulmonary vein isolation; RAMVR, robo replacement; RAMVS, robotic-assisted mitral valve surgery; RMVR, robotic mitral valve repair/replacement; SD, standard deviation; SMVR, sternotomy mitral repair/replacement; TERMR, totally endoscopic robotic mitral valve repair.*								

Table 2
Baseline Characteristics

Study ID	Study Group	Sample Size, n	Age, mean (SD)	Male, n (%)	NYHA Class 3–4 (%)	Diabetes mellitus (%)	Hypertension (%)	COPD (%)	Ejection fraction (%)	ICU stay (days/hours)
Chien et al. 2025	Robotic MVR (Unmatched)	113	60.13 ± 12.72	57 (50.44)	NR	16.81	25.43	10.62	NR	4.39 days
	Conventional MVR (Unmatched)	5,547	62.98 ± 12.97	2,585 (46.60)	NR	17.97	31.24	14.46	NR	9.11 days
Chikwe et al. 2025	Robotic MV surgery	1,411	63 (54–70)*	922 (65.3)	13	NR	NR	NR	62 (60–66)*	NR
Coyan et al. 2018	Robotic MVR	91	62 (20–85)*	52 (57.1)	33	11	62.6	5.5	60 (5–75)*	27.5 hours
	Conventional MVR	91	62 (21–86)*	50 (54.9)	36.3	12.1	62.6	7.7	58 (30–75)*	34.0 hours
Franke et al. 2022	Isolated Robotic MVR	96	58.8 ± 11.1	75 (78.1)	NR	NR	NR	NR	NR	41 hours
	Complex Robotic MVR	86	67.5 ± 11.2	60 (69.8)	NR	NR	NR	NR	NR	60.5 hours
Giroletti et al. 2023	Robotic MV surgery	149	59.1 ± 13.3	105 (70.5)	26.9	4.1	45.6	0	65 (60–68)*	40 hours
Güllü et al. 2021	Robotic MV repair	60	48.3 ± 15	23 (38.3)	10	NR	10	6.7	62.4 ± 5.4	21.4 hours
Hadaya et al. 2025	Robotic MV repair	4,002	61.3 ± 12.2	2,712 (67.8)	NR	NR	60.1	11.6	NR	4 days
	Conventional MV repair	36,736	61.8 ± 11.9	22,854 (62.2)	NR	NR	62	14.5	NR	5 days
Kadiroğulları et al. 2026	Robotic MVR (all)	233	48.4 ± 13.9	117 (50.2)	NR	14.6	17.7	13.7	56.4 ± 8.2	18 hours
Kam et al. 2010	Robotic MVR	107	57.6 ± 13.7	76 (71.0)	NR	0.9	30.2	NR	NR	36.7 hours
	Conventional MVR	40	61.6 ± 11.2	33 (82.5)	NR	2.6	38.5	NR	NR	45.5 hours
Mihaljevic et al. 2014	Robotic MV repair	473	56 ± 10	372 (78.6)	10.1	NR	38.5	3.2	60 ± 4.5	NR
	Complete Sternotomy	227	62 ± 11	161 (70.9)	19.3	NR	48.7	8.4	59 ± 5.4	NR
Noda et al. 2025	Robotic MVR	110	60 (52–67)*	74 (67.3)	0	49.1	82.7	1.8	NR	NR
	Mini-MVR	1,430	60 (51–69)*	906 (63.4)	1.7	91	87.6	3.6	NR	NR
Paul et al. 2015	Robotic MV repair	631 (matched)	59.3	436 (68.8)	NR	6.6	44.2	8.7	NR	4 days
	Non-robotic MV repair	631 (matched)	59.2	444 (70.4)	NR	5.4	43.3	9.2	NR	6 days
Sandoval et al. 2024	Robotic MV repair (Centre 1)	62	63 (54–67)*	49 (79.0)	11.3	3.2	46.8	NR	NR	1 days
	Robotic MV repair (Centre 2)	62	60 (48–67)*	47 (75.8)	29	8.1	32.3	NR	NR	1 days
*Median (IQR) reported instead of mean (SD). Abbreviations: NR = Not reported; MI = Myocardial Infarction; COPD = Chronic Obstructive Pulmonary Disease; IPTW = Inverse Probability of Treatment Weighting; LOS = Length of Stay; TERMR = Totally Endoscopic Robotic Mitral Valve Repair; MIMVS = Minimally Invasive Mitral Valve Surgery; CUSUM = Cumulative Sum Analysis										

Study ID	Study Group	Sample Size, n	Age, mean (SD)	Male, n (%)	NYHA Class 3–4 (%)	Diabetes mellitus (%)	Hypertension (%)	COPD (%)	Ejection fraction (%)	ICU stay (days/hours)
Seo et al. 2019	Robotic MV repair	175	61 ± 13	77 (44)	NR	7	41	5	60.4 ± 8.4	NR
	Open MV repair	259	62 ± 15	135 (52)	NR	10	51	13	57.6 ± 12	NR
Suri et al. 2013	Robotic MV repair (post-2009)	119	55.6 ± 11.3	92 (77.3)	0.8	0.8	40.3	5	64.6 ± 7.3	9.3 hours
	Open MV repair (post-2009)	74	58.1 ± 13.2	51 (68.9)	4.1	0	33.8	4.1	62.7 ± 8.2	24.3 hours
Yaffee et al. 2014	TERMR	32	56.0 ± 12.6	23 (71.9)	NR	NR	NR	NR	NR	4 days
*Median (IQR) reported instead of mean (SD). Abbreviations: NR = Not reported; MI = Myocardial Infarction; COPD = Chronic Obstructive Pulmonary Disease; IPTW = Inverse Probability of Treatment Weighting; LOS = Length of Stay; TERMR = Totally Endoscopic Robotic Mitral Valve Repair; MIMVS = Minimally Invasive Mitral Valve Surgery; CUSUM = Cumulative Sum Analysis										

Risk of bias assessment

Newcastle-Ottawa Scale evaluations classified eleven studies as good quality (seven to nine stars) and six studies as fair quality (five to six stars). No studies were classified as poor quality. The most common limitations were absence of a non-exposed cohort in learning curve studies and insufficient follow-up duration for cost outcomes. Detailed quality assessments are presented in Fig. 2.

Total cost outcomes

Total operative cost was reported in five studies, including a total of 91,541 participants. The pooled analysis demonstrated no statistically significant difference between robotic and conventional approaches (MD 1619.99 USD, 95% CI -2344.75 to 5584.74; $p = 0.423$), with substantial heterogeneity ($I^2 = 99.3\%$; $p < 0.001$) (Fig. 3A). However, in the LOO analysis, exclusion of Hadaya et al. (2025) revealed that the robotic approach had a significantly lower total cost compared to the conventional approach (MD -775.11 USD, 95% CI -1169.68 to -380.55; $p < 0.001$), with no observed heterogeneity ($I^2 = 0\%$) (Fig. S1).

Operative and postoperative costs

Operative cost was reported in three studies with a total of 1753 participants. The robotic approach was significantly associated with higher operative cost (MD 2144.16 USD, 95% CI 1216.12 to 3072.19; $p < 0.001$) with substantial heterogeneity ($I^2 = 92.9\%$; $p < 0.001$) (Fig. 3B). In the LOO analysis, excluding Suri et al. (2013) reduced the heterogeneity to $I^2 = 0\%$ while the effect remained significant (Fig. S2).

Postoperative cost was reported in two studies, including a total of 1560 participants. The robotic approach was associated with lower postoperative costs compared with the conventional approach (MD -556.01 USD, 95% CI -872.09 to -239.93; $p < 0.001$), with no evidence of heterogeneity ($I^2 = 0\%$; $p = 0.611$) (Fig. 3B).

Learning curve outcomes: cross-clamp time

Two studies ($N = 152$ participants) compared the learning phase versus the proficiency phase in terms of cross-clamp time. The pooled analysis showed that the learning phase had a higher cross-clamp time compared to the proficiency phase; however, this effect was not statistically significant (MD 52.20 minutes, 95% CI -7.18 to 111.58; $p = 0.085$) and showed substantial heterogeneity ($I^2 = 96.9\%$; $p < 0.001$) (Fig. 4A).

Two studies ($N = 1617$ participants) compared the proficiency phase versus the mastery phase. The estimates from individual studies varied widely, and the pooled analysis showed no significant difference in cross-clamp time (MD 11.23 minutes, 95% CI -46.69 to 69.14; $p = 0.704$), with substantial heterogeneity ($I^2 = 99.4\%$; $p < 0.001$) (Fig. 4B).

Learning curve outcomes: cardiopulmonary bypass time

Regarding cardiopulmonary bypass time, two studies ($N = 152$ participants) compared the learning phase versus the proficiency phase. The pooled analysis showed that the learning phase was associated with longer CPB time compared to the proficiency phase, though this difference did not reach statistical significance (MD 74.33 minutes, 95% CI -0.95 to 149.59; $p = 0.053$) with high heterogeneity ($I^2 = 96.9\%$; $p < 0.001$) (Fig. 5A).

Two studies ($N = 1617$ participants) compared the proficiency phase versus the mastery phase in terms of CPB time. Estimates varied substantially across studies, and the pooled analysis showed no statistically significant effect (MD 2.69 minutes, 95% CI -67.77 to 73.15; $p = 0.940$) with a wide confidence interval and substantial heterogeneity ($I^2 = 99.1\%$; $p < 0.001$) (Fig. 5B).

Discussion

Pooled analysis of total operative cost from five studies (over 91,000 patients) showed no significant difference between robotic and conventional approaches, though with substantial heterogeneity across trials. This finding aligns with prior single-center propensity-matched studies that reported cost neutrality between robotic and sternotomy-based mitral valve repair when comprehensive cost accounting was used (12,14). For instance, one study using activity-based costing that included robotic depreciation, maintenance, and supplies found no difference in total costs between robotic and sternotomy approaches (12). Similarly, another group demonstrated that after implementing system efficiencies such as rapid ventilator weaning and shorter ICU stays, the median cost of robotic repair became equivalent to that of open surgery (14).

A closer look at the data reveals that the overall null result was driven largely by a single large study. Removing that study from the analysis shifted the findings: the robotic approach then showed significantly lower total costs with no residual heterogeneity. This suggests that after technical proficiency has been established, the remaining evidence consistently favors cost neutrality or even modest savings with robotic surgery. One analysis found that robotic repair was associated with an 11% reduction in direct costs and a 24% reduction in room costs, mainly due to shorter hospital stays (13). The strong influence of a single study highlights the importance of sensitivity analyses in meta-analyses of cost data, where methodological differences in cost accounting are inherently high (32,33).

Breaking costs down by phase shows a clear pattern. Robotic surgery had significantly higher operative costs, a well-established finding driven by disposable instrument costs (about \$1,500 per case), longer operative times, and amortized capital investment (11,34). One study reported that direct technical operative costs were 19-37% higher for robotic surgery than for sternotomy or thoracotomy (11). On the other hand, robotic surgery was associated with significantly lower postoperative costs, reflecting downstream savings from shorter ICU and hospital stays, fewer transfusions, and lower readmission rates (12–14). This pattern, higher upfront expense offset by lower post-procedural resource use, has been a consistent theme in the robotic cardiac surgery literature (16).

The heterogeneity in cost analyses deserves attention. Studies vary widely in their accounting methods, from hospital charge data and administrative claims to detailed activity-based costing (32). Whether capital depreciation and maintenance costs are included, the annual procedure volume over which fixed costs are spread, and whether indirect societal costs like earlier return to work are factored in all affect the reported cost difference (11,34). One analysis showed that excluding amortization costs made robotic surgery only marginally more expensive (about 600 per case), but including amortization raised the incremental cost to roughly 3,700 per case (34). Moreover, reimbursement structures differ across countries, limiting the generalizability of cost findings from one healthcare system to another (15).

Learning Curve Outcomes

Learning curve analyses showed substantial reductions in both cross-clamp time and cardiopulmonary bypass time when comparing the learning phase to the proficiency phase, though these reductions did not reach statistical significance. The magnitude of improvement is clinically meaningful and aligns with prior reports. One study found that the learning curve matured at approximately 30 cases, with significant reductions in both bypass and cross-clamp times between the first and second 30-case cohorts (16). Another group used cumulative sum analysis to identify three phases, learning (first 27 cases), proficiency (cases 28–92), and mastery (93 cases onward), with roughly 93 procedures needed to achieve operative stability and take on more complex patients (17).

The lack of statistical significance in the pooled analysis likely reflects the small number of available studies, limited sample sizes, and extreme statistical heterogeneity. Wide confidence intervals point to insufficient statistical power and substantial variation across studies in how learning phases were defined, what case volume thresholds were used, how complex the cases were within each phase, and heterogeneous operator experience. Notably, comparisons between proficiency and mastery phases also showed no significant differences in procedural times. This suggests that once proficiency is achieved, further time reductions may plateau or become masked by the inclusion of increasingly complex cases as surgeons expand their indications (17,35).

An important emerging finding is that the learning curve may be reduced or even eliminated when a surgeon joins an established robotic program. One study showed that subsequent surgeons entering an experienced robotic mitral program achieved better-than-predicted outcomes from the start, with no measurable learning curve defined by worse-than-predicted clinical results (28). In that program, the institutional learning curve peaked at case 94, after which risk-adjusted outcomes were consistently better than predicted (28). This suggests that the learning curve is not just an individual surgeon phenomenon. It is heavily shaped by institutional infrastructure, team experience, mentorship, and standardized training pathways. This concept has now been formalized in a recent expert consensus document on robotic cardiac surgical training (36).

The relationship between cost and the learning curve

The connection between cost and the learning curve is a key consideration for programs thinking about adopting robotic surgery. Higher operative costs during the early learning phase, driven by longer operative times, greater resource use, and possibly higher complication rates, should diminish as proficiency improves (13,14). One analysis showed progressive reductions in room time, surgery time, and cross-clamp time as surgeon experience accumulated, along with corresponding decreases in overall costs (13). The finding that postoperative cost savings are consistent across studies, while operative cost heterogeneity remains high, suggests that the operative phase, the component most influenced by the learning curve, is the main driver of cost variability. This has practical implications: institutions should expect higher initial costs that will likely converge toward or below those of conventional approaches as operative efficiency improves with experience.

Limitations

This analysis has several limitations. Few studies were available for each comparison which limited statistical power and precluded subgroup or meta-regression analyses. Heterogeneity was high across most pooled estimates, reflecting differences in study design, cost accounting, healthcare

systems, learning curve definitions, and patient populations. While we used random-effects models, the extent of heterogeneity still limits interpretation of the pooled estimates.

We did not adjust cost data for inflation or purchasing power parity across countries or time periods. Most studies were retrospective and single-center, introducing potential selection bias. Learning curve definitions varied widely. Key cost components (capital depreciation, maintenance, societal costs) were reported inconsistently, preventing a full cost-of-ownership analysis. Lastly, publication bias may exist, though was not formally assessed due to limited number of studies per each outcome.

Conclusion

This meta-analysis demonstrates that robotic mitral valve surgery is cost-neutral relative to conventional approaches. Higher operative costs from disposable instruments and longer procedure times are consistently offset by lower postoperative costs due to shorter hospital stays, fewer transfusions, and reduced readmissions. The learning curve directly influences cost trajectories, with operative times and costs converging toward conventional methods as experience accumulates. Structured training within established programs may substantially reduce or eliminate the learning curve for subsequent surgeons. These findings support the economic viability of robotic mitral valve surgery when institutions commit to adequate case volumes, standardized training, and perioperative system innovations. However, substantial heterogeneity across studies, driven by variable cost accounting and inconsistent learning curve definitions, underscores the need for future research using standardized economic methods and uniform proficiency benchmarks.

Declarations

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Figures

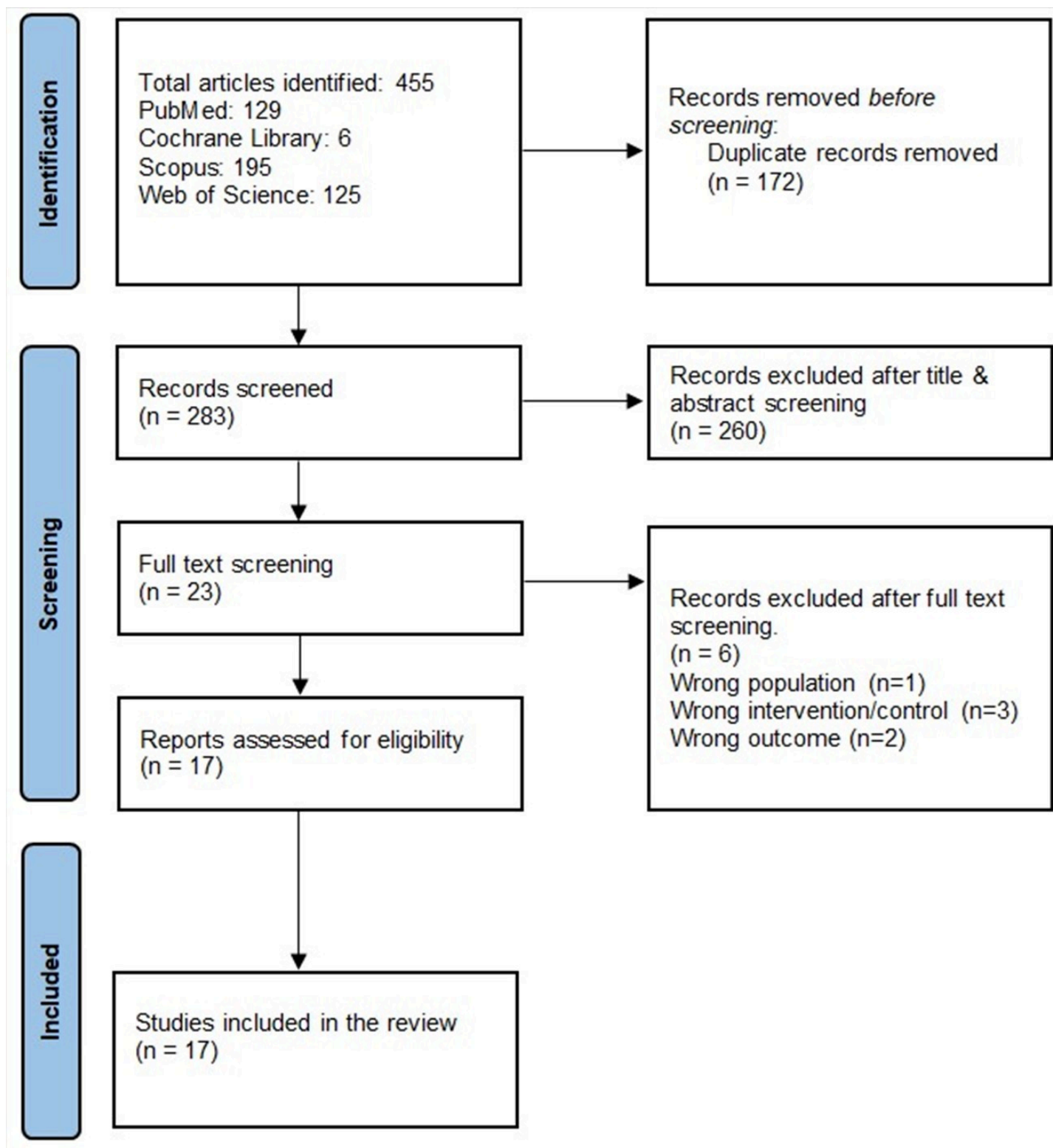


Figure 1

PRISMA flowchart

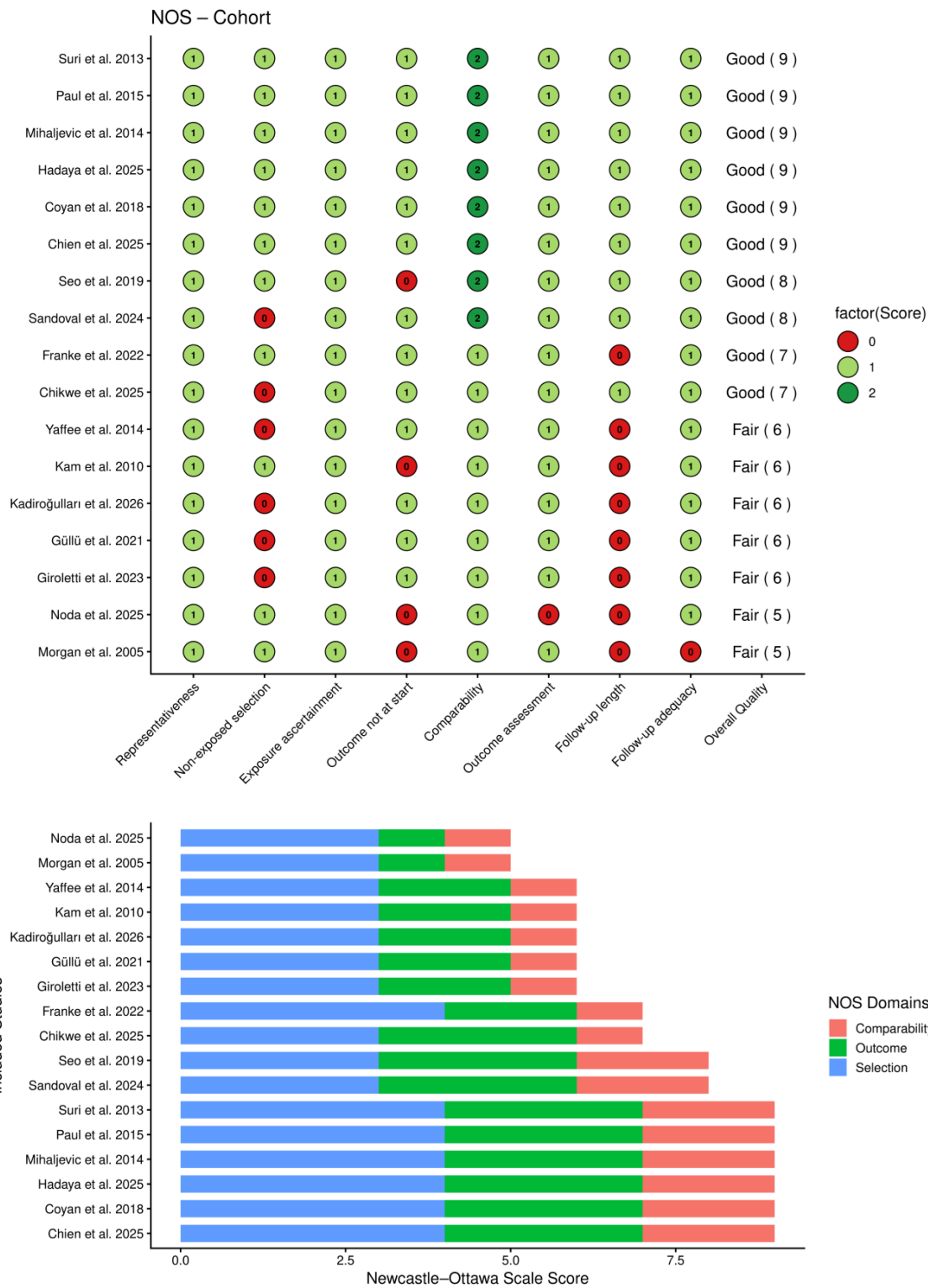
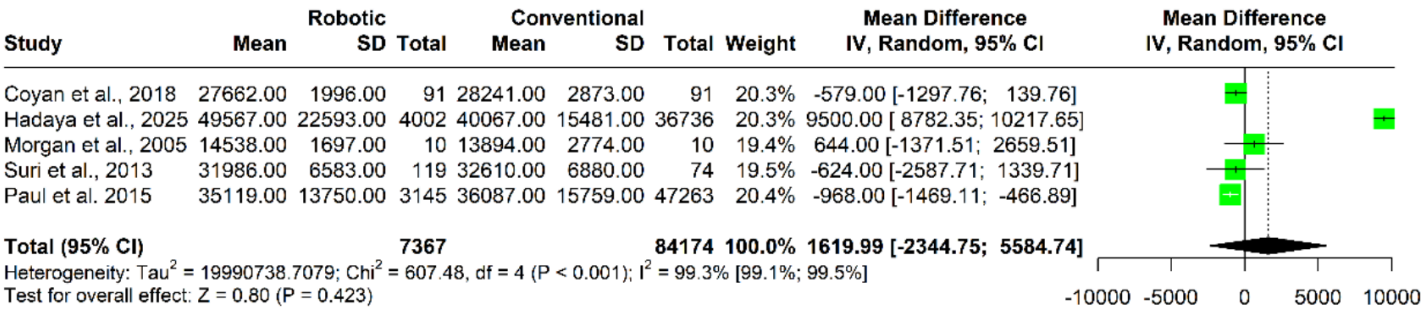


Figure 2

Newcastle-Ottawa scal assessment for included studies

A



B

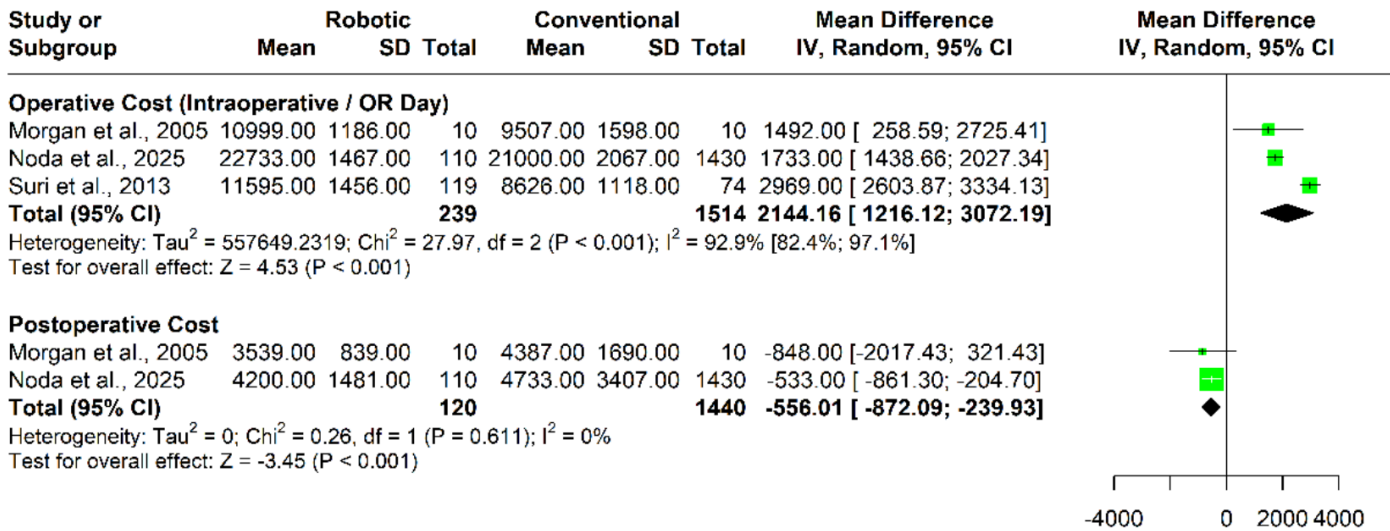
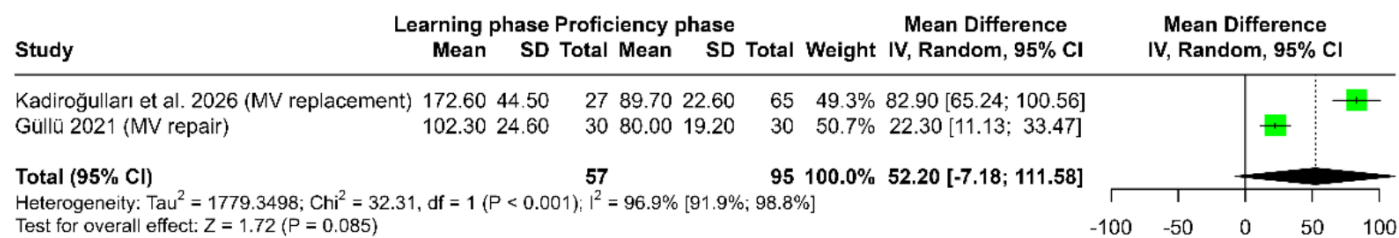


Figure 3

A: Forest plot for total cost (USD). Figure 3B: Forest plot for operative cost (top panel) and postoperative cost (bottom panel) in USD.

A



B

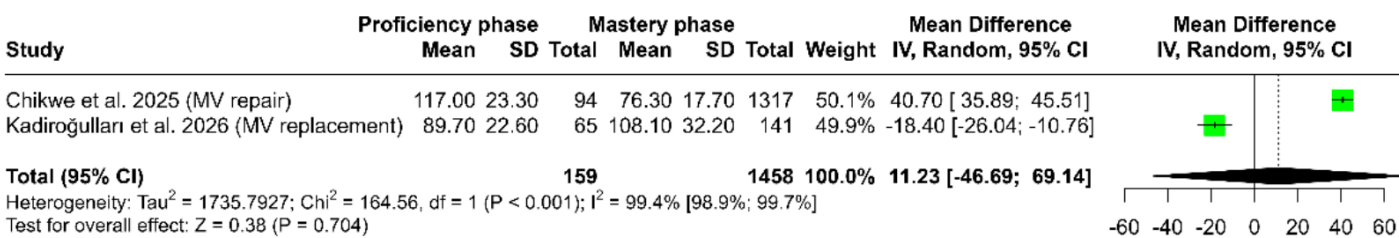
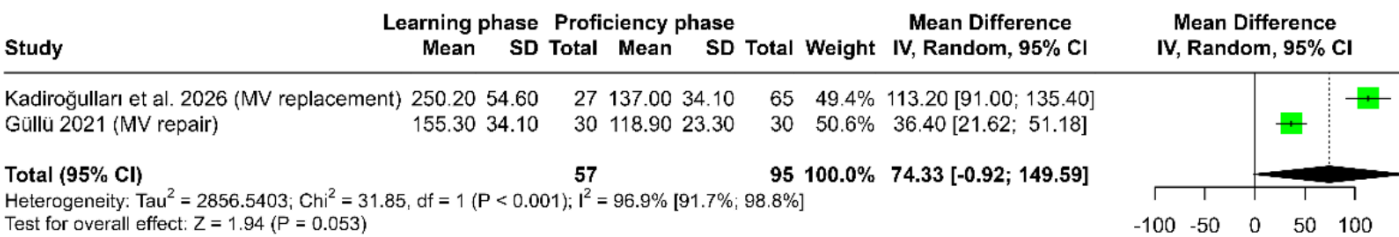


Figure 4

A: Forest plot for cross-clamp time (minutes) comparing the learning phase versus proficiency phase. B: Forest plot for cross-clamp time (minutes) comparing proficiency phase versus mastery phase.

A



B

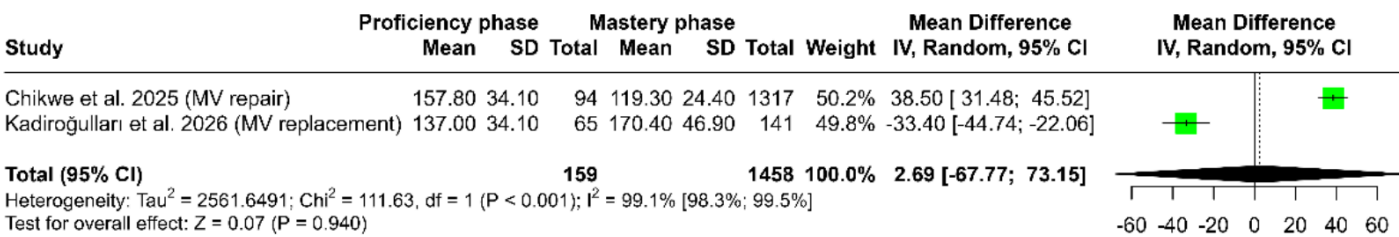


Figure 5

A: Forest plot for cardiopulmonary bypass time (minutes) comparing the learning phase versus proficiency phase. B: Forest plot for cardiopulmonary bypass time (minutes) comparing proficiency phase versus mastery phase

Image not available with this version

Figure 6

A: Forest plot for cardiopulmonary bypass time (minutes) comparing the learning phase versus proficiency phase. B: Forest plot for cardiopulmonary bypass time (minutes) comparing proficiency phase versus mastery phase

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