Heart Surgery Forum 2025; 28(2): E219–E227
doi: 10.59958/hsf.8217

Systematic Review

Efficacy and Safety of Robot-Assisted and Sternotomy for Mitral Valve Repair in the Treatment of Mitral Regurgitation: A Systematic Review and Meta-Analysis

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Submitted: 12 November 2024 Revised: 17 December 2024 Accepted: 8 January 2025 Published: 24 February 2025

Abstract

Background: Current research comparing the efficacy of robot-assisted mitral valve repair with sternotomy presents inconsistent results. This meta-analysis compares the advantages and disadvantages of robot-assisted mitral valve repair versus sternotomy, providing clinicians with a clearer reference for surgical decision-making. **Methods**: We systematically searched the PubMed, Embase, and Cochrane Library databases for studies published from inception to September 2021. Cohort studies were included where the observation group underwent robot-assisted surgery, and the control group received sternotomy. We excluded repeated publications, studies lacking full text, incomplete data, animal studies, and reviews/systematic reviews. Data were analyzed using STATA 15.1. **Results**: The pooled results showed that the operation time (weighted mean difference (WMD) = 43.95, 95% confidence interval (CI): 36.53–51.36), aortic cross-clamp time (WMD = 26.72, 95% CI: 15.48–37.96), and cardiopulmonary bypass time (WMD = 39.50, 95% CI: 29.52–49.47) were significantly longer for robotic surgery compared to the sternotomy group. However, robotic surgery resulted in significantly shorter lengths of intensive care unit (ICU) stay (WMD = –25.43, 95% CI: –37.21–13.66) and hospital stay (WMD = –1.58, 95% CI: –2.26– –0.89) compared to sternotomy. The blood transfusion rate was significantly lower in the robotic surgery group (odds ratio (OR) = 0.66, 95% CI: 0.47–0.94). Furthermore, the mortality rate was significantly lower for robotic surgery (OR = 0.32, 95% CI: 0.17–0.60). **Conclusion**: Although robot-assisted mitral valve repair requires longer cross-clamp time, cardiopulmonary bypass time, and operation time compared to sternotomy, it results in shorter ICU and hospital stays, a lower blood transfusion rate, and a reduced mortality rate.

Keywords

robot-assisted; sternotomy; mitral valve repair; mitral regurgitation; meta-analysis

Introduction

Mitral valve repair has emerged as the preferred treatment for mitral regurgitation due to its significant advantages over mitral valve replacement in improving patient outcomes [1]. Traditionally, sternotomy has been the standard approach for mitral valve repair surgery [2]. However, robot-assisted surgery has revolutionized the surgical landscape, offering enhanced flexibility and precision by providing surgeons with an expanded surgical field. A growing body of research has reported on the use of robotic systems in mitral valve repair surgeries [3]. The first robotic mitral valve repair was conducted in 1998, and the technology was approved by the US Food and Drug Administration (FDA) in 2002 [4,5]. Currently, the da Vinci Surgical System remains the sole robotic platform approved by the FDA for cardiac surgery [5].

Robot-assisted surgery offers several advantages, such as smaller incisions, improved visualization through three-dimensional cameras, and increased dexterity, which allows for a greater range of motion and tremor reduction. However, despite these benefits, robotic surgery has certain limitations, including a steep learning curve, the need for peripheral cannulation, and higher operating times and equipment costs [6,7]. While robotic surgery is associated with potential advantages such as reduced short-term mortality, fewer blood transfusions, and shorter postoperative hospital stays [8,9], the evidence remains inconclusive. Many studies comparing robotic-assisted surgery to traditional methods are retrospective, often with small sample sizes and lacking multi-center data, resulting in conflicting findings. Given the current lack of consensus on the comparative merits of the two surgical approaches and the absence of quantitative evaluations of postoperative outcomes and safety, there is a pressing need for further investigation. To address this gap, the present study conducts a meta-analysis to evaluate and compare the perioperative data, postoperative outcomes, and safety of robotic-assisted mitral valve repair versus sternotomy. The goal is to comprehensively analyze both techniques, offering valuable insights to guide clinical decision-making and treatment planning.

Methods

Literature Inclusion and Exclusion Criteria

The inclusion criteria for this study were the cohort study design, patients diagnosed with mitral valve disease via echocardiography and computed tomography (CT), the observation group undergoing robot-assisted surgery, the control group undergoing sternotomy, and studies published in English. Exclusion criteria included duplicate publications, studies without full text or sufficient data for extraction, animal studies, reviews, and systematic reviews.

Search Strategy

A comprehensive search was performed using the PubMed, Embase, and Cochrane Library databases to identify studies published from the inception of these databases until September 2021. The primary search terms used included "Robotic", "Robot", "Robot-assisted" AND "Sternotomy" AND "Mitral valve regurgitation", and "Mitral valve insufficiency".

Literature Screening and Data Extraction

Two researchers independently conducted the literature search, screening, and data extraction, with a third researcher consulted in cases of uncertainty or disagreement to reach a consensus. The extracted data included study characteristics (author, publication year, study region, study design, and sample size), patient demographics (age, sex, ejection fraction, and NYHA classification), and outcome indicators (operation time, aortic cross-clamp time, cardiopulmonary bypass time, intensive care unit (ICU) stay, total hospital stay, blood transfusion rate, incidence of postoperative complications, and mortality rate).

Literature Quality Assessment

Two researchers independently assessed the quality of the included studies using the Newcastle–Ottawa Scale (NOS) for cohort studies [10], which evaluates three domains: Selection of study subjects (4 points), comparability between groups (2 points), and outcome measurement (3 points), with a total possible score of 9 points. Studies scoring $\geq$7 were classified as high quality, while those scoring $<$7 were considered lower quality. Any disagreements were resolved through discussion or consultation with a third researcher. The analysis followed the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [11] (**Supplementary Table. 1**).

Data Synthesis and Statistical Analysis

Data analysis was performed using STATA (Version 15.1: StataCorp LLC, College Station, TX, USA), applying the weighted mean difference (WMD) with a 95% confidence interval (CI) to compare operation time, aortic cross-clamp time, cardiopulmonary bypass time, ICU stay duration, and total hospital stay between the robotic-assisted surgery and sternotomy groups. Heterogeneity was assessed using the I-Square (I^2) test: if $p \geq 0.1$ and $I^2 \leq 50\%$, homogeneity was assumed, and a fixed-effects model was used; if $p < 0.1$ and $I^2 > 50\%$, significant heterogeneity was identified, and sensitivity analysis was conducted to explore sources. If heterogeneity persisted, a random-effects model or descriptive analysis was applied. Publication bias was assessed using funnel plots and Egger's test.

Results

The Results of the Literature Search

In this study, 224 articles were initially retrieved from the database. After removing duplicates, 131 articles remained. After reviewing the titles and abstracts, 83 studies were selected. Nine studies were ultimately included in the meta-analysis (Fig. 1).

Baseline Characteristics and Quality Assessment of the Included Studies

A total of nine cohort studies were included in this meta-analysis. The sample size of patients varied from 50 to 1106, with a total of 3627 patients, including 1833 patients in the robotic surgery group and 1744 patients in the sternotomy group. All patients were middle-aged or older individuals ($>$50 years old). The ejection fraction and NYHA classification between the robotic surgery and sternotomy groups were comparable. Based on the NOS score, the quality assessment showed scores above 7 for all studies, meeting the required standards (Table 1, Ref. [8,9,12–18]).

Meta-Analysis Results

Operative Data

We initially examined operative data, including operation time, aortic cross-clamp time, and cardiopulmonary bypass time. Given the absence of significant heterogene-

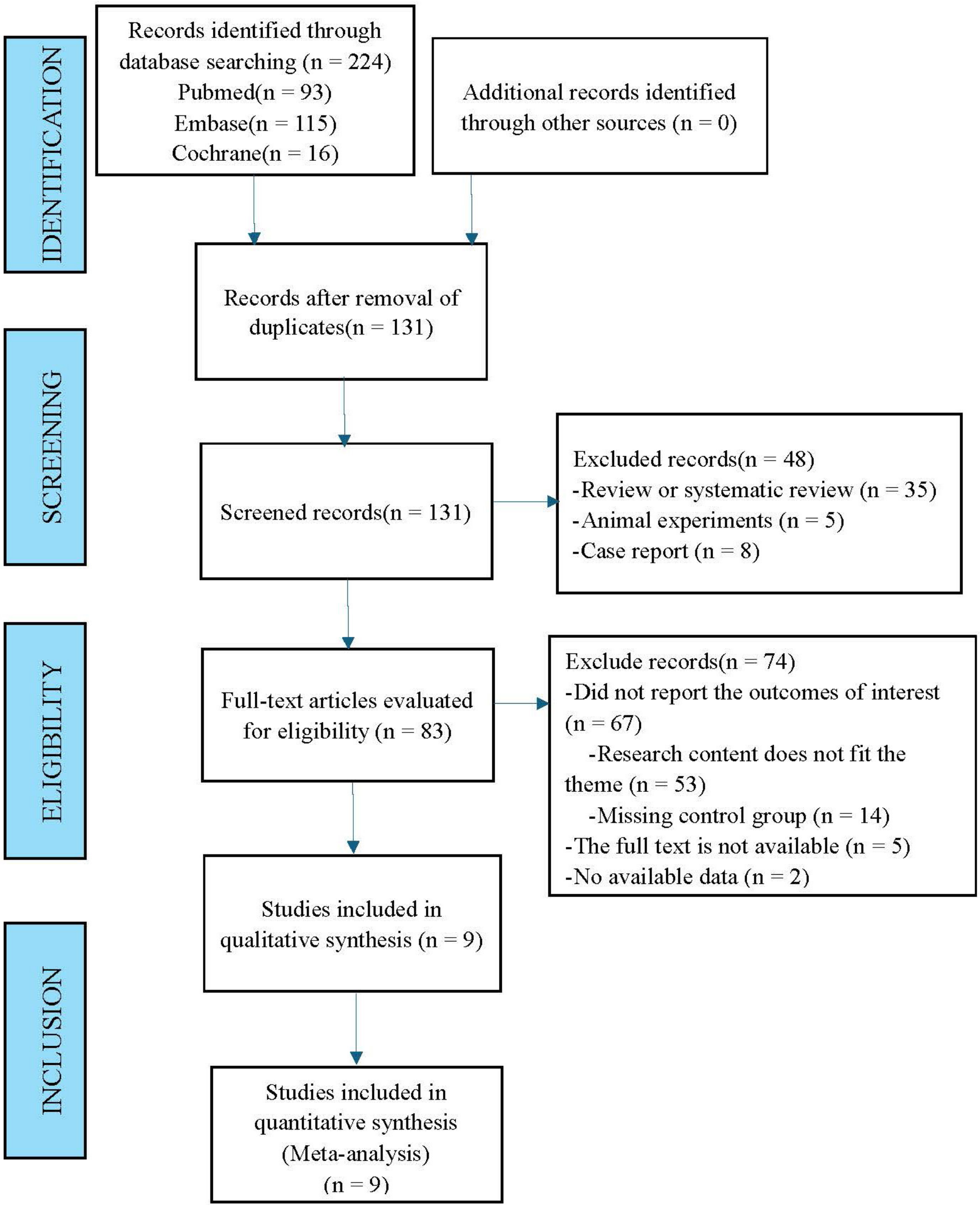

Fig. 1. Flow diagram for selection of studies.

ity (I^2 = 45.4%, p = 0.139), a meta-analysis was performed using a fixed-effects model. The pooled results revealed that the operation time for robotic surgery was significantly longer than that for the sternotomy group (WMD = 43.95 min, 95% CI: 36.53–51.36 min, p = 0.000) (Fig. 2A). Furthermore, the pooled results indicated that both aortic cross-clamp time (WMD = 26.72 min, 95% CI: 15.48–37.96 min, p = 0.000; I^2 = 96.3%, p = 0.000) and cardiopulmonary bypass time (WMD = 39.50 min, 95% CI: 29.52–49.47 min, p = 0.000; I^2 = 91.6%, p = 0.000) were significantly longer in the robotic surgery group compared to the sternotomy group (Fig. 2B,C).

Short-Term Outcomes

Next, we examined short-term outcomes, including length of ICU stay, length of hospital stay, and blood transfusion rate. The pooled results indicated that the length of ICU stay (WMD = –25.43 hours, 95% CI: –37.21 to –13.66 hours, p = 0.000; I^2 = 95.4%, p = 0.000) and the length of hospital stay (WMD = –1.58 days, 95% CI: –2.26– –0.89 days, p = 0.000; I^2 = 93.5%, p = 0.000) were significantly shorter in the robotic surgery group compared to the sternotomy group (Fig. 3A,B). Additionally, the pooled results showed that the blood transfusion rate (OR = 0.66, 95% CI: 0.47–0.94, p = 0.019; I^2 = 62.1%, p = 0.032) was significantly lower in the robotic surgery group than in the sternotomy group (Fig. 3C).

Table 1. Baseline characteristics and quality assessment of the included studies.

Author	Year	Research design	Study area	Number of patients		Age (year)		Sex (female/male)		Ejection fraction (%)		NYHA		NOS score
				Robotic surgery	Sternotomy	Robotic surgery	Sternotomy	Robotic surgery	Sternotomy	Robotic surgery	Sternotomy	Robotic surgery	Sternotomy	
Folliguet *et al*. [12]	2006	Retrospectively cohort	France	25	25	59.4 ± 11.2	60.4 ± 11.1	9/16	8/17	0.57	0.55	Class I/II/III: 17/6/2	Class I/II/III: 16/5/4	8
Woo and Nacke [9]	2006	Retrospectively cohort	USA	25	39	60.0 ± 3.0	60.0 ± 2.0	8/17	15/24	/	/	/	/	7
Kam *et al*. [13]	2010	Retrospectively cohort	Australia	107	40	57.6 ± 13.7	61.6 ± 11.2	31/76	7/33	/	/	/	/	7
Suri *et al*. [14]	2011	Retrospectively cohort	USA	95	95	54.9 ± 11.0	55.7 ± 14.1	22/73	19/76	65.3 ± 6.6	65.3 ± 5.8	Class I and II: 85	Class I and II: 86	7
Stevens *et al*. [8]	2012	Retrospectively cohort	USA	447	377	57.0 ± 13.0	60.0 ± 14.0	168/279	197/180	/	/	/	/	8
Kesävuori *et al*. [15]	2018	Retrospectively cohort	Finland	142	142	59.0 ± 10.8	59.4 ± 10.0	27/115	29/113	/	/	Class I/II/III/IV: 18/63/56/5	Class I/II/III/IV: 13/61/63/5	7
Hawkins *et al*. [16]	2018	Retrospectively cohort	USA	314	314	61 (53–69)	61 (53–69)	127/187	136/178	60 (55–63)	60 (55–65)	/	/	7
Wang *et al*. [17]	2018	Retrospectively cohort	USA	503	503	71.9 ± 5.6	72.0 ± 5.5	194/309	203/300	59.5 ± 8.3	60.0 ± 8.3	/	/	7
Seo *et al*. [18]	2019	Retrospectively cohort	USA	175	259	61.0 ± 13.0	62.0 ± 15.0	98/77	124/135	60.4 ± 8.4	57.6 ± 12.0	/	/	8

NOS, Newcastle–Ottawa Scale.

Safety

Finally, we assessed the safety of surgery, including the incidence of postoperative complications and mortality rate. Given the absence of significant heterogeneity (I^2 = 0.0%, p = 0.912), a meta-analysis was performed using a fixed-effects model. The pooled results indicated no significant difference in the incidence of postoperative complications between robotic surgery and sternotomy (OR = 1.02, 95% CI: 0.65–1.58, p = 0.935) (Fig. 4A). However, the mortality rate was significantly lower in the robotic surgery group compared to the sternotomy group (OR = 0.32, 95% CI: 0.17–0.60, p = 0.000; I^2 = 0.0%, p = 0.717) (Fig. 4B).

Sensitivity Analysis

We performed sensitivity analysis by eliminating each included study individually and a summary analysis of the remaining studies. Our research results found that none of the studies had an excessive impact on the results of the meta-analysis, which suggests that the results of this meta-analysis are stable and reliable.

Publication Bias

Fig. 5 shows an asymmetric funnel plot for this study. Egger's test p-value was 0.524, indicating no obvious publication bias.

Discussion

Mitral valve repair remains the gold standard for treating severe symptomatic mitral regurgitation. Advances in technology, surgical techniques, and perioperative care have allowed complex valve repairs while reducing the risk of death for most patients [19]. Robotic technology has been used in mitral valve repair for nearly two decades and has received different acceptance among surgeons [20]. However, current research results comparing the efficacy of mitral valve repair with robot-assisted surgery and sternotomy for mitral valve repair are inconsistent. Therefore, this meta-analysis included nine studies with 3627 patients and compared the indicators of robot-assisted and sternotomy for mitral valve repair in the treatment of mitral regurgitation, aiming to guide clinical applications.

Notably, longer aortic cross-clamp and cardiopulmonary bypass (CPB) times have traditionally been associated with adverse outcomes such as myocardial injury and systemic inflammatory responses [21,22]. However, the current study's finding of shorter ICU and hospital stays suggests that the benefits of minimally invasive surgery, such as reduced surgical trauma and quicker recovery, might counterbalance the risks associated with prolonged operative durations. This aligns with findings from Yan *et al*. [23], who demonstrated that despite longer CPB

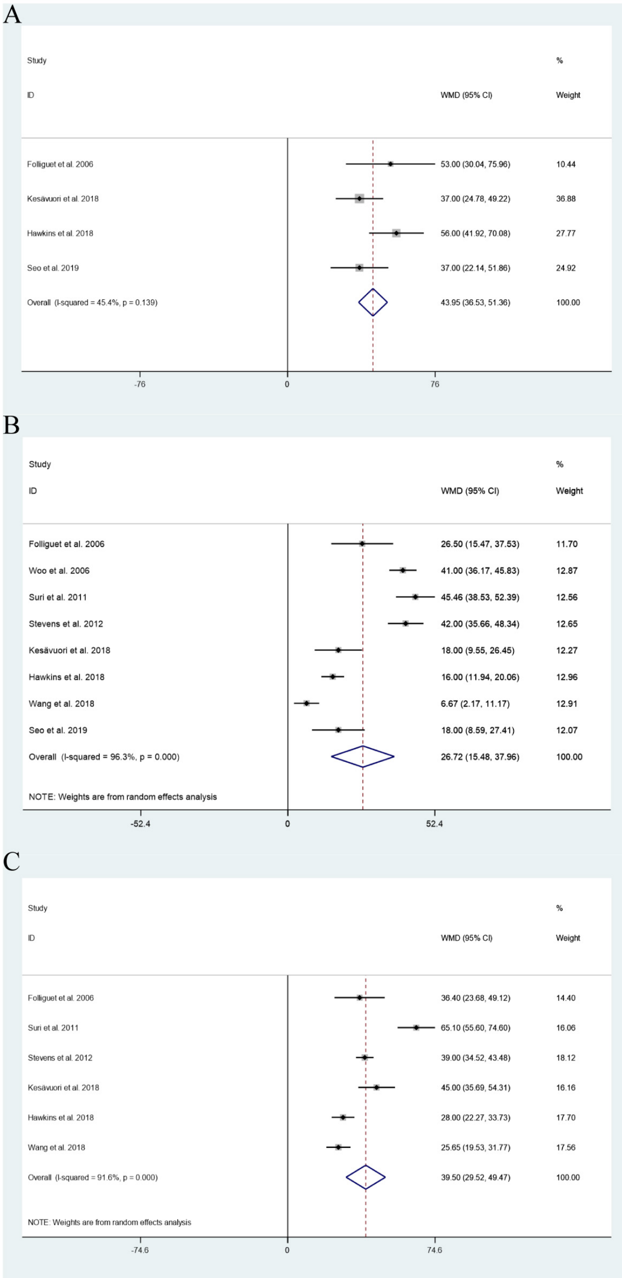

Fig. 2. Comparison of operative data, including operation time (A), aortic cross-clamp time (B), and cardiopulmonary bypass time (C) between the robotic surgery and sternotomy groups. WMD, weighted mean difference; 95% CI, 95% confidence interval.

times in robotic-assisted surgery, patients still experienced favorable recovery profiles compared to conventional sternotomy.

The significantly shorter ICU and hospital stays observed in the robotic surgery group highlight the potential for enhanced postoperative recovery with minimally invasive approaches. Reduced trauma to the chest wall, smaller incisions, and less postoperative pain in robotic-assisted procedures likely contribute to these favorable outcomes

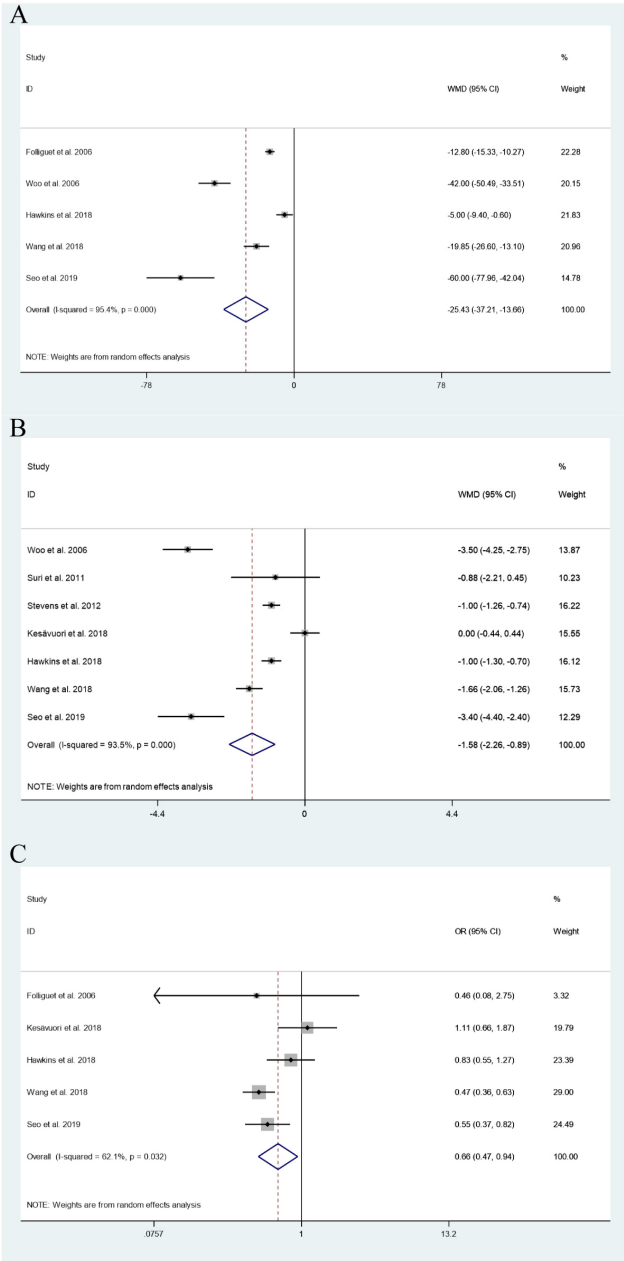

Fig. 3. Comparison of length of ICU stay (A), hospital stay (B), and blood transfusion rate (C) between robotic surgery and sternotomy groups. OR, odds ratio.

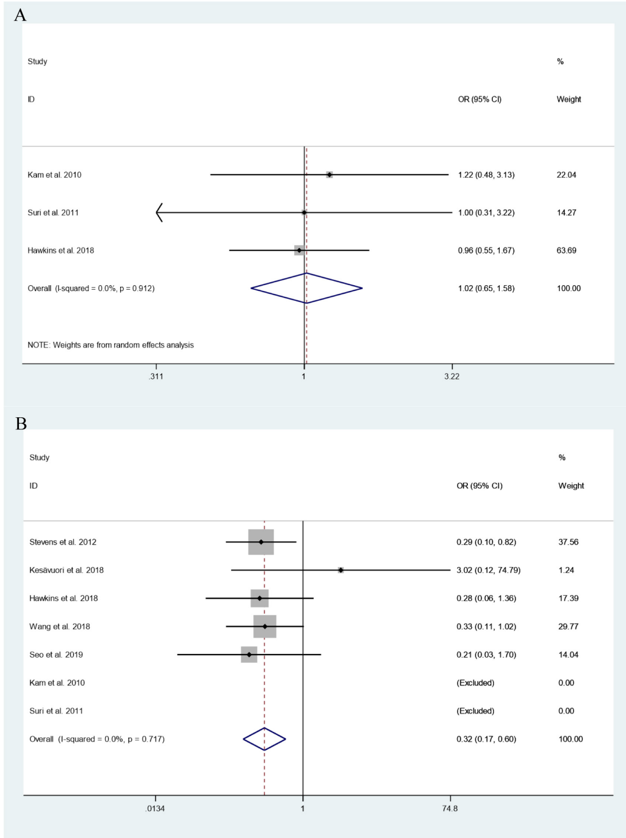

Fig. 4. Comparison of postoperative complication incidence (A) and mortality rate (B) between the robotic surgery and sternotomy groups.

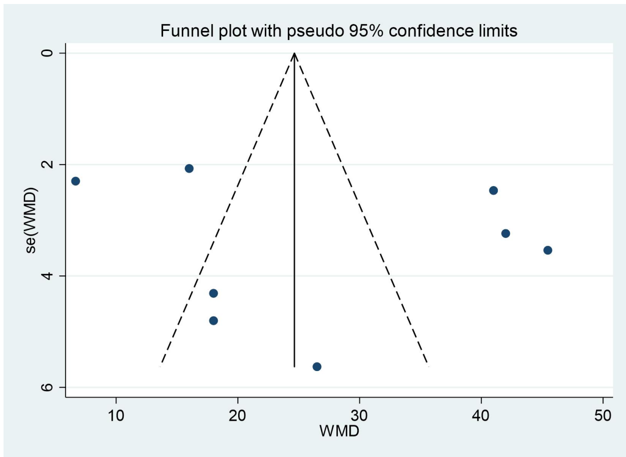

Fig. 5. Funnel plot for evaluating publication bias in this meta-analysis.

[24]. These findings are consistent with prior studies that emphasize the role of robotic surgery in expediting recovery and minimizing the duration of hospital resource utilization [25,26].

The lower blood transfusion rates observed in the robotic group further underscore the advantages of reduced operative trauma. Blood loss during robotic cardiac surgery is often minimal due to smaller incisions and the precision of robotic instrumentation [27]. Similarly, a study by McAlpine *et al*. [28] reported that robotic-assisted cardiac surgery significantly reduces the need for blood transfusions compared to sternotomy, leading to fewer transfusion-related complications and improved patient outcomes. This finding has important implications for clinical practice, as minimizing blood transfusions can reduce healthcare costs and the risk of transfusion-related adverse events.

The lack of significant differences in the incidence of postoperative complications between robotic surgery and sternotomy demonstrates that robotic-assisted approaches are comparably safe. This supports findings from other meta-analyses, such as those by De Jesus *et al*. [29], which report similar rates of postoperative complications between the two surgical approaches. Importantly, the significantly lower mortality rate in the robotic group highlights the potential for improved long-term survival when minimally invasive techniques are employed. This is particularly relevant in high-risk patients, where reduced surgical trauma and faster recovery may mitigate the impact of comorbidities [30].

While the lower mortality rate is promising, considering the prolonged operative and cardiopulmonary bypass (CPB) times, these findings should be interpreted cautiously. A balance must be struck between achieving the benefits of minimally invasive surgery and managing the challenges associated with longer operative durations. Thus, further studies are needed to explore whether reduced trauma and enhanced recovery outweigh the risks of extended CPB time, particularly in specific patient subgroups.

The findings of this meta-analysis contribute to the growing body of evidence supporting robotic-assisted cardiac surgery as a safe and effective alternative to conventional sternotomy. While longer operation times remain a limitation, the benefits of shorter ICU and hospital stays, lower blood transfusion rates, and reduced mortality suggest that robotic surgery can improve patient recovery and reduce healthcare resource utilization. These advantages are particularly relevant in the current healthcare climate, where minimizing hospital stays and optimizing resource allocation are critical.

From a clinical perspective, these results emphasize the importance of institutional experience and the surgical learning curve. As proficiency with robotic systems increases, operation times are likely to decrease, further enhancing the benefits of robotic-assisted surgery. Future research should focus on identifying patient subgroups that would benefit the most from robotic surgery and exploring strategies to optimize operative efficiency, such as advanced preoperative planning and improved robotic technology.

The current study addresses a notable gap in the literature regarding the comparative outcomes of robotic surgery and sternotomy, particularly regarding short-term recovery and safety. While previous studies have reported similar findings, they were often limited by small sample sizes or significant heterogeneity [31,32]. However, with its rigorous methodology and pooled data, this meta-analysis provides robust evidence to inform clinical decision-making. Nonetheless, additional research is needed to assess long-term outcomes, including quality of life and cost-effectiveness, to establish further the role of robotic surgery in cardiac care.

Over the past few decades, robotic-assisted mitral valve surgery has emerged as a promising alternative to traditional sternotomy, offering significant benefits in terms of postoperative outcomes such as reduced blood transfusion rates, shorter ICU and hospital stays, and faster recovery. However, the increased upfront costs of robotic surgery, particularly the capital costs of purchasing robotic systems, have raised concerns about its economic sustainability. Despite this, several studies suggest that while robotic mitral valve replacement (MVR) may have higher procedural costs, these are often offset by lower postoperative costs and quicker recovery times, leading to overall savings [33–36]. Furthermore, as surgical experience with robotic systems increases and technology improves, the cost-effectiveness of robotic MVR is expected to improve. While the capital costs associated with robotic surgery remain challenging, the potential for broader applications in higher-risk patients and the growing demand for minimally invasive procedures may drive future adoption, ultimately supporting the continued use of robotic technology in mitral valve surgery. Thus, despite initial concerns about cost, the long-term value of robotic surgery, in terms of patient outcomes and societal savings, appears promising and justifies its ongoing use and development.

Our study has limitations: (1) Including non- randomized controlled trial (RCT) studies potentially promotes selection bias. Additionally, because each patient must decide whether to accept robotic surgery, it is difficult to achieve double blindness. Therefore, without randomization and adequate patient matching, the existing research on robotic surgery is imperfect; (2) there was heterogeneity in the results of this study; however, many of the data included in the study were not refined, such as the level of hypertension, type of diabetes, pathological type of valve, level of cardiac function, etc., so we could not perform subgroup analysis to determine sources of heterogeneity accurately, meaning these variables are all potential causes of heterogeneity.

Conclusion

Although robot-assisted mitral valve repair has longer aortic blocking, cardiopulmonary bypass, and operation times than sternotomy, the ICU stay and hospitalization times are shorter, and the blood transfusion and complication rates are lower. At the same time, we can foresee that the advantages of robotic surgery will become more obvious as doctors continue to accumulate experience and the robotics technology is upgraded.

Availability of Data and Materials

The datasets are available from the corresponding author on reasonable request.

Author Contributions

TF and YFH conceived the study, and wrote the manuscript. HYG participated in data collection, JTL, CQ and FX participated in data analysis. TJC conceived the idea, analyzed the data and revised the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript. All authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Ethics Approval and Consent to Participate

Not applicable.

Acknowledgment

Not applicable.

Funding

This research received no external funding.

Conflict of Interest

The authors declare no conflict of interest.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.59958/hsf.8217.

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