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Comparative efficacy of totally thoracoscopic, mini-thoracotomy, and mini-sternotomy approaches in aortic valve replacement

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Aortic valve replacement (AVR) is a critical procedure for patients with aortic valve diseases. This study compares the effectiveness of three minimally-invasive surgical approaches for AVR: totally thoracoscopic (TT), right anterior mini-thoracotomy, and upper mini-sternotomy. We analyzed retrospective data from 130 patients who underwent one of these surgeries, focusing on various factors such as duration of hospital stay, operation time, times for cardiopulmonary bypass and aortic cross-clamping, postoperative complications, levels of cardiac biomarkers, pain intensity using the Visual Analog Scale, and mid-term survival rates. Results show that while the TT method had the longest operation times, it also had the shortest hospital stays and faster pain reduction post-surgery. Although the TT group initially showed higher cardiac biomarker levels after surgery, these levels normalized by the third day, similar to the other groups. There were no significant differences in mid-term survival and major adverse cardiac and cerebrovascular event (MACCE) rates among the groups. These findings suggest that the TT method, despite longer surgical times, offers a quicker initial recovery, making it a viable option for AVR.

Keywords Aortic valve replacement, Totally thoracoscopic approach, Postoperative outcomes, Pain management, Mid-term survival, Cardiac biomarkers

Abbreviations

AVR	Aortic valve replacement
TT	Totally thoracoscopic
MT	Mini-thoracotomy
MS	Mini-sternotomy
CPB	Cardiopulmonary bypass
ACC	Aortic cross-clamp
CK-MB	Creatine kinase MB
cTnT	Cardiac troponin T
VAS	Visual analog scale
MACCE	Major adverse cardiac and cerebrovascular events
AI	Aortic insufficiency
RAMT	Right anterior mini-thoracotomy
PUS	Partial upper sternotomy

Aortic valve replacement (AVR) is a pivotal surgical intervention in the management of aortic valve diseases, offering a life-saving solution for conditions like stenosis and regurgitation[1]. Traditionally, AVR has been performed through open-chest procedures, but with the evolution of surgical techniques, the focus has shifted towards less invasive methods. This paradigm shift aims to reduce patient morbidity, enhance recovery, and provide equivalent, if not superior, long-term outcomes[2].

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The recent advancement in this field has been the development of minimally invasive surgical approaches, which include totally thoracoscopic (TT)[3], right anterior mini-thoracotomy (MT), and upper mini-sternotomy (MS), each with its unique methodology and potential benefits[4]. The minimally invasive approaches for AVR, particularly the TT method, represent a significant step forward in reducing the physical burden of cardiac surgery. While minimally invasive cardiac surgery has been widely used for atrioventricular valve lesions, the adoption of TT in AVR is relatively less explored. TT, along with right anterior MT and upper MS, minimizes surgical trauma, potentially leading to shorter hospital stays, less postoperative pain, and quicker recovery[5]. These approaches, however, come with their own sets of challenges, such as longer operation times and specific technical demands, making the choice of the surgical technique critical based on individual patient characteristics and surgical goals.

The primary objective of our study is to evaluate and compare the efficacy and outcomes of three surgical approaches for AVR. By analyzing and comparing these methods, the study aims to provide valuable insights into the benefits and limitations of each approach, contributing to the optimization of patient care in AVR surgeries.

Results

Baseline demographic and clinical characteristics

In our retrospective study comparing MS, MT, and TT approaches for AVR, we found no significant differences in most baseline demographic and clinical characteristics across the 130 patients, and the flowchart of patient selection and data analysis was shown in Fig. 1. The average ages were 54.02, 49.67, and 51.67 years, and the BMIs were 23.77, 22.79, and 24.35 kg/m^2 for the MS, MT, and TT groups, respectively, with no significant age or BMI differences ($P > 0.1$). Cardiac function indicators, including Left Ventricular Ejection Fraction and Dimension, were comparable across the groups ($P > 0.1$). Gender distribution and the prevalence of comorbid conditions like hypertension, diabetes, and smoking habits were similarly not significantly different ($P > 0.2$). The only notable variation was in the etiology of aortic valve disease, where congenital causes (bicuspid aortic valve) were more prevalent in the TT group, showing a significant difference ($P = 0.041$). This baseline similarity allows for a more equitable comparison of surgical outcomes among the three approaches (Table 1).

Operative data and postoperative in-hospital outcomes

In evaluating operative data and postoperative outcomes, significant differences were observed between the MS, MT, and TT groups in AVR (Table 2). The TT group experienced notably shorter hospital stays (6.53 days) and ICU stays (1.20 days) compared to MS (8.26 days, 2.23 days) and MT (7.77 days, 1.84 days), with these differences being statistically significant ($P < 0.001$ for hospital stays, $P < 0.001$ for ICU stays). The length of mechanical ventilation was also significantly shorter in the TT group (11.06 h) compared to MS (15.40 h) and MT (14.14 h) ($P < 0.001$).

Operation durations varied significantly, with the TT approach taking the longest (249.85 min), followed by MT (221.60 min) and MS (198.83 min) ($P < 0.001$). Similarly, CPB and ACC times were significantly longer for TT (CPB: 150.93 min, ACC: 111.95 min) compared to MS (CPB: 85.21 min, ACC: 65.72 min) and MT (CPB: 102.14 min, ACC: 75.65 min) ($P < 0.001$). Postoperative complications, including respiratory complications (lung infection and respiratory failure), cardiocerebral events, and other common postoperative issues, showed no significant differences across the groups ($P > 0.2$). The TT group, however, had significantly lower 24-h chest drainage and blood loss ($P < 0.001$), with reduced transfusion requirements for red blood cells and plasma compared to MS ($P < 0.03$). No in-hospital deaths were reported in any group (Table 2).

Post-operative CK-MB and cTnT levels

The Kruskal–Wallis test was used to analyze differences in post-operative cardiac biomarkers among three groups over the first three postoperative days (POD), shown in Fig. 2. For CK-MB levels on POD 1, the median values were 24.3 for MS, 26.3 for MT, and 34.1 for TT, with the differences being statistically significant ($P = 0.0047$). On POD 2 and POD 3, the median CK-MB levels were similar across all groups (MS: 9.1 and 3.5; MT: 9.1 and 3.2; TT: 9.0 and 2.7), with no significant differences ($P = 0.4746$ for POD 2, $P = 0.4918$ for POD 3). cTnT levels on POD 1 revealed medians of 0.4 for both MS and MT, and 0.6 for TT, with this day showing a statistically significant difference ($P = 0.0017$). On POD 2, the medians were 0.3 for MS and MT, and 0.4 for TT, and on POD 3, the medians were consistent at 0.3 across all groups. The differences in cTnT levels on POD 2 and POD 3 were not statistically significant ($P = 0.1814$ for POD 2, $P = 0.1209$ for POD 3). These results suggest that while there were significant differences in the immediate post-operative period for both CK-MB and cTnT levels, with TT showing higher medians, these differences normalized by the second and third postoperative days with no significant differences between the surgical approaches.

VAS scores

The post-operative pain was assessed by VAS scores (Fig. 3). On the first day after surgery, median pain levels were highest in the MT group at 7(6, 8), followed by MS at 6(5, 7), and lowest in the TT group at 4(3, 5), with the differences being highly significant ($P < 0.0001$). By the second day, the MT group's pain remained high at 6(6, 7), MS at 6(5, 7), and TT at 4(3, 4), with significant differences persisting ($P < 0.0001$). On the third day, the scores began to diverge, with TT showing a decrease to 3(2, 4), MS at 5(4, 6), and MT at 6(5, 7), again with significant differences ($P < 0.0001$). However, by the three-month mark, the pain levels converged to low values with no significant differences: MS at 1(1, 2), MT at 2(1, 2), and TT at 2(1, 2) ($P = 0.3011$). The dashed lines connecting the medians of each group over time illustrate the overall downward trend in VAS scores, indicating recovery and pain reduction across all surgical approaches.

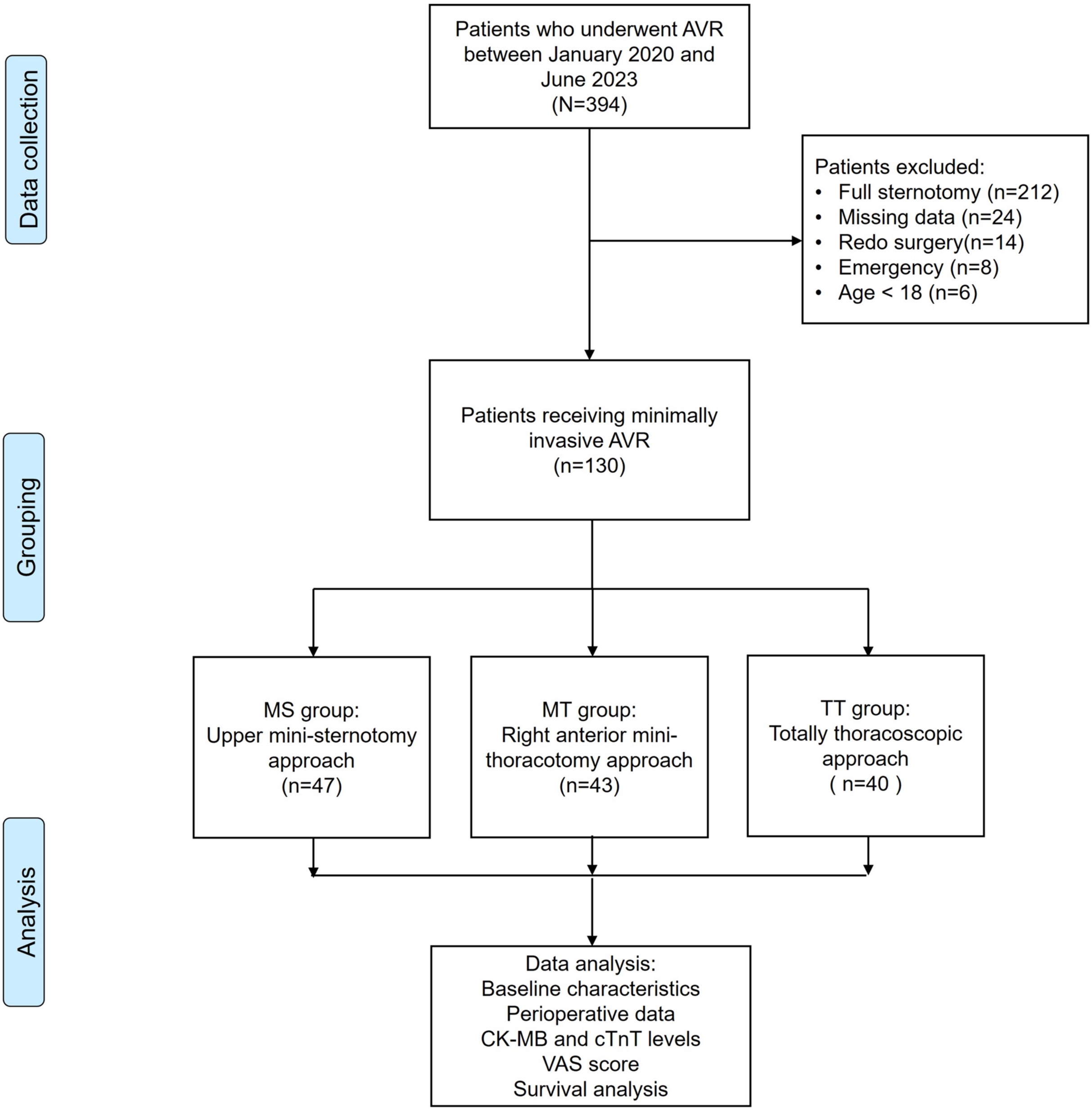

Figure 1. Flowchart of patient selection and data analysis.

Mid-term outcomes of three different groups
Mid-term outcomes for the MS, MT, and TT groups showed comparable overall survival and freedom from MACCE over a 12-month period (Fig. 4). In the MS group, there was 1 event by month 10 with a survival rate of 91.1%; the MT group experienced 1 event by month 5 with a survival rate of 96.55%; and the TT group had 1 event by month 3 with a survival rate of 96.88%. For MACCE, the MS group had 1 event by month 1 and a survival rate of 86.1% by month 10; the MT group reported 1 event by month 5 with a survival rate of 91.5% by month 8; and the TT group experienced 1 event by month 2 with a survival rate of 94.3% by month 3. Overall, there was no significant difference in survival or MACCE rates among the groups ($p = 0.86$ for survival, $p = 0.74$ for MACCE).

Discussion
In the discussion of our study, we highlight the significant findings related to the efficacy and outcomes of the three minimally invasive surgical approaches for AVR. Our analysis revealed that while the TT approach entailed longer operation durations, it was associated with shorter hospital and ICU stays, indicating a potentially quicker recovery period. Postoperative pain levels, as assessed by VAS scores, decreased more rapidly in the TT group within the first three days after surgery. Furthermore, early postoperative cardiac biomarker levels, specifically CK-MB and cTnT, showed significant differences on the first day; however, these differences normalized by the third postoperative day across all groups. Importantly, the mid-term survival rates and MACCE incidence were

Group	Level	MS (n = 47)	MT (n = 43)	TT (n = 40)	*P*	SMD
Age, years		54.02 (11.04)	49.67 (13.40)	51.67 (16.02)	0.314	0.22
BMI, kg/m^2		23.77 (3.70)	22.79 (2.55)	24.35 (4.07)	0.123	0.305
LVEF, %		58.47 (9.81)	61.16 (9.03)	61.20 (7.39)	0.249	0.202
LVD, cm		5.51 (1.19)	5.31 (1.34)	5.82 (0.77)	0.133	0.306
Gender, n (%)	Female	14 (29.8)	12 (27.9)	7 (17.5)	0.379	0.195
	Male	33 (70.2)	31 (72.1)	33 (82.5)		
Type, n (%)	AI	20 (42.6)	24 (55.8)	22 (55.0)	0.548	0.258
	AS	13 (27.7)	12 (27.9)	9 (22.5)		
	AS + AI	14 (29.8)	7 (16.3)	9 (22.5)		
Etiology, n (%)	Congenital	19 (40.4)	19 (44.2)	21 (52.5)	0.041	0.464
	Degenerative	20 (42.6)	22 (51.2)	19 (47.5)		
	Infective	8 (17.0)	2 (4.7)	0 (0.0)		
NYHA grade III/IV, n (%)		5 (10.6)	3 (7.0)	4 (10.0)	0.819	0.086
CKD, n (%)		1 (2.1)	1 (2.3)	1 (2.5)	0.993	0.017
HBP, n (%)		16 (34.0)	9 (20.9)	15 (37.5)	0.219	0.247
DM, n (%)		4 (8.5)	1 (2.3)	5 (12.5)	0.213	0.267
Stroke history, n (%)		3 (6.4)	3 (7.0)	1 (2.5)	0.619	0.142
COPD, n (%)		0 (0.0)	2 (4.7)	0 (0.0)	0.128	0.208
Smoking, n (%)		23 (48.9)	21 (48.8)	14 (35.0)	0.339	0.19

Table 1. Comparison of patients' baseline demographic and clinical characteristics. MS, Mini-Sternotomy; MT, Mini-Thoracotomy; TT, Totally Thoracoscopic; SMD, Standardized Mean Difference; n, Number of Patients; SD, Standard Deviation; BMI, Body Mass Index; LVEF, Left Ventricular Ejection Fraction; LVD, Left Ventricular Dimension; AI, Aortic Insufficiency; AS, Aortic Stenosis; AS + AI, Combined Aortic Stenosis and Aortic Insufficiency; NYHA, New York Heart Association grade; CKD, Chronic Kidney Disease; HBP, Hypertension; DM, Diabetes Mellitus; a COPD, Chronic Obstructive Pulmonary Disease.

comparable among the TT, MT, and MS groups, underscoring the relative safety and efficacy of these surgical techniques for AVR.

The development and evolution of AVR have been characterized by significant advancements in surgical techniques and patient outcomes. The field of AVR has witnessed innovations like the adoption of smaller incisions without compromising surgical outcomes[1], reflecting the trend towards less invasive procedures while maintaining the efficacy of traditional methods. The choice of minimally invasive surgical approaches for AVR is determined during preoperative medical staff meetings, considering patient-specific factors such as age, comorbidities, vascular status, and EuroSCORE II. This tailored approach ensures the selection of the most suitable technique for each individual patient[2].

The study by Xu et al. aligns with our findings that the thoracoscopic (TT) approach could reduce postoperative pain and improve short-term quality of life, highlighting the benefits of less invasive techniques[6]. This is further supported by the findings of Liu et al., which observed reduced pain in patients undergoing minimally invasive AVR, consistent with our observation of quicker pain reduction in the TT group[7]. Additionally, the mid-term outcomes in our study, such as survival rates and MACCE incidence, were similar across all groups, resonating with the findings of Lan et al. who reported no significant difference in mid-term outcomes between minimally invasive and conventional approaches[8]. Our study also found that the MS approach resulted in shortest CPB and cross-clamp times compared to partial upper sternotomy (PUS)/MT and TT, different fromSeitz et al. and Olds et al[9,10]. These studies noted that the MT approach led to decreased operative times and shorter hospital stays, supporting its efficacy. The reason for this discrepancy is that we had accumulated extensive experience with conventional sternotomy AVR, which allowed for faster adaptation and shorter operative times in the MS group. The MT group served as a transitional phase towards developing expertise in the TT approach, which involved a steeper learning curve and consequently longer operative times initially. Our center performs relatively fewer mini-thoracotomy procedures, which may explain the longer bypass and cross-clamp times for MT. Despite this, we successfully adopted the TT AVR technique and demonstrated improved performance over time. The general benefits of minimally invasive AVR, such as reduced perioperative blood loss and improved cosmetic outcomes, were also discussed by Jahangiri et al., though these advantages can be offset by longer bypass and cross-clamp times[2]. Bakhtiary et al. compared midterm outcomes of isolated AVR via right anterior mini-thoracotomy (RAMT) and PUS in 202 matched pairs from 694 cases. RAMT resulted in shorter CPB and hospitalization times, with a marginally higher 4-year survival rate compared to PUS, though not statistically significant. The study suggests RAMT as a preferable first-line option for its efficiency, while PUS remains a viable alternative for patients not suited to RAMT[11]. However, we didn't find a significant difference between MT and MS group in CPB and hospitalization times.

The initial elevation in cardiac biomarkers, specifically CK-MB and cTnT, observed in the TT group, can be attributed to the longer duration of operation and CPB time. The intricate nature of the TT approach necessitates a more extended period of surgical manipulation and CPB support, which can contribute to a transient increase

Group	Level	MS (n = 47)	MT (n = 43)	TT (n = 40)	*P*	SMD
Hospital stays, d		8.26 (2.43)	7.77 (2.17)	6.53 (1.58)	0.001	0.57
ICU stay, d		2.23 (0.87)	1.84 (1.09)	1.20 (0.41)	< 0.001	0.903
Mechanical ventilation length, h		15.40 (4.15)	14.14 (4.02)	11.06 (4.56)	< 0.001	0.674
Operation duration, min		198.83 (30.41)	221.60 (32.42)	249.85 (60.33)	< 0.001	0.792
CPB time, min		85.21 (34.14)	102.14 (39.24)	150.93 (29.71)	< 0.001	1.305
ACC time, min		61.72 (21.83)	75.65 (22.00)	111.95 (26.82)	< 0.001	1.39
Prosthetic valve type, n (%)	Mechanical valve	13 (27.7)	8 (18.6)	13 (32.5)	0.34	0.215
	Bioprosthetic valve	34 (72.3)	35 (81.4)	27 (67.5)		
Implant size, n (%)	21 mm	5 (10.6)	4 (9.3)	5 (12.5)	0.985	0.09
	23 mm	35 (74.5)	32 (74.4)	28 (70.0)		
	25 mm	7 (14.9)	7 (16.3)	7 (17.5)		
Respiratory complication, n (%)		7 (14.9)	8 (18.6)	6 (15.0)	0.867	0.066
Prolonged ventilation, n (%)		6 (12.8)	6 (14.0)	5 (12.5)	0.978	0.029
LCOS requiring MCS, n (%)		0 (0.0)	1 (2.3)	1 (2.5)	0.561	0.152
Cardiocerebral events, n (%)		1 (2.1)	3 (7.0)	2 (5.0)	0.544	0.158
Poor healing wound, n (%)		1 (2.1)	1 (2.3)	0 (0.0)	0.635	0.147
Conversion to sternotomy, n (%)		0 (0.0)	1 (2.3)	0 (0.0)	0.361	0.145
III AVB, n (%)		1 (2.1)	1 (2.3)	0 (0.0)	0.635	0.147
Paravalvular leakage, n (%)		0 (0.0)	0 (0.0)	1 (2.5)	0.322	0.151
Unplanned Reopeartion, n (%)		1 (2.1)	0 (0.0)	0 (0.0)	0.411	0.139
New onset AF, n (%)		5 (10.6)	7 (16.3)	5 (12.5)	0.724	0.111
Post-LVEF, %		60.40 (4.90)	58.98 (5.68)	57.97 (5.23)	0.108	0.311
Post-LVEDD, cm		4.78 (0.88)	4.72 (0.85)	4.68 (0.64)	0.855	0.082
Mean pressure gradient, mmHg		10.91 (5.32)	11.47 (5.59)	12.78 (5.98)	0.31	0.22
Peak flow velocity, m/s		2.39 (0.42)	2.23 (0.47)	2.34 (0.53)	0.277	0.224
24 h Chest Drainage, mL		518.09 (173.25)	395.12 (178.10)	302.00 (235.50)	< 0.001	0.73
Blood loss, mL		453.19 (186.33)	432.56 (142.63)	297.50 (145.86)	< 0.001	0.664
RBC, n (%)		10 (21.3)	5 (11.6)	1 (2.5)	0.029	0.41
Plasma, n (%)		15 (31.9)	6 (14.0)	1 (2.5)	0.001	0.57
Platelet, n (%)		1 (2.1)	1 (2.3)	0 (0.0)	0.635	0.147
In-hospital death, n (%)		0 (0.0)	0 (0.0)	0 (0.0)	NaN	< 0.001

Table 2. Operative data and postoperative in-hospital outcomes. MS, Mini-Sternotomy; MT, Mini-Thoracotomy; TT, Totally Thoracoscopic; d, days; h, hours; min, minutes; CPB, Cardiopulmonary Bypass; ACC, Aortic Cross-Clamp; AVB, Atrioventricular Block; AF, Atrial Fibrillation; LVEF, Left Ventricular Ejection Fraction; LVEDD, Left Ventricular End-Diastolic Dimension; RBC, Red Blood Cells.

in cardiac biomarker levels as a response to myocardial stress. However, it is important to note that despite this initial rise, the biomarker levels demonstrated a rapid normalization by the second postoperative day. This quick recovery indicates a resilience of the myocardial tissue to the surgical stress, which is not indicative of permanent damage or dysfunction. Moreover, the transient nature of this biomarker elevation does not appear to correlate with the efficacy or mid-term outcomes of the procedure. By day 3, the CK-MB and cTnT levels across all groups had equalized, suggesting that the initial stress response was effectively managed and resolved without mid-term sequelae. This finding is supported by the comparable mid-term survival rates and MACCE incidence among the TT, MT, and MS groups. Such data reinforces the concept that while cardiac biomarkers serve as an important early indicator of myocardial strain, their transient elevation in the context of TT AVR does not undermine the procedural efficacy nor compromise mid-term clinical outcomes.

The primary difference between two-port and three-port complete thoracoscopic cardiac surgery lies in the number and configuration of ports used. In the two-port approach, there is typically one main operating port and a second port that accommodates the thoracoscope, ACC, and left ventricular vent catheter[12]. This method may reduce the number and size of incisions, potentially leading to less postoperative pain and a quicker recovery. The three-port method adds an auxiliary port for the ACC and left ventricular vent catheter. The study by Liu et al. retrospectively compared the two-port and three-port approaches for totally thoracoscopic mitral valve replacement to assess their feasibility, safety, and short-term outcomes. Analyzing data from 330 patients, with 103 in the two-port group and 227 in the three-port group, they performed propensity score matching to eliminate selection bias, resulting in 71 matched pairs. Their findings showed no significant differences in CPB time, ACC time, mechanical ventilation duration, ICU stay, or postoperative chest drainage between the two groups. The study concluded that both approaches are safe and effective for mitral valve replacement, with no significant advantage in operative times or perioperative outcomes[7]. In our study, all patients in TT group adopted the three

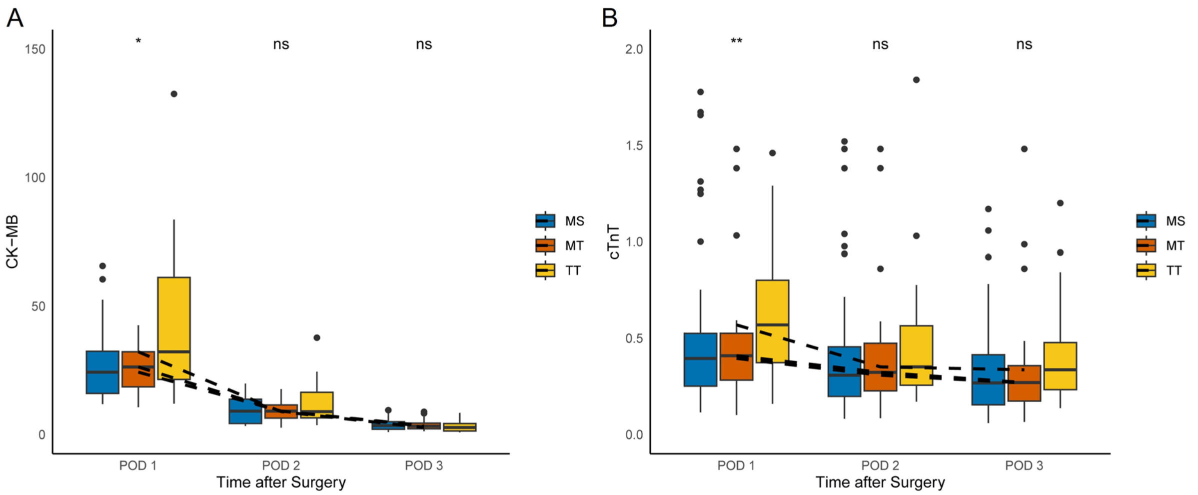

Figure 2. Post-operative Cardiac Biomarker Levels by Surgical Approach. (**A**) the levels of CK-MB; (**B**) cTnT levels on postoperative days 1, 2, and 3 (POD 1, POD 2, POD 3) for MS (blue), MT (orange), and TT (yellow) groups. Box plots depict median values and interquartile ranges, with whiskers extending to the rest of the distribution except for outliers, which are represented as individual points. Statistically significant differences between the groups on POD 1 are indicated with asterisks (* for $P<0.05$, ** for $P<0.01$), while 'ns' denotes a non-significant difference on PODs 2 and 3. The dashed lines connect the medians of each group across the time points, illustrating the trend in biomarker levels during the initial postoperative period.

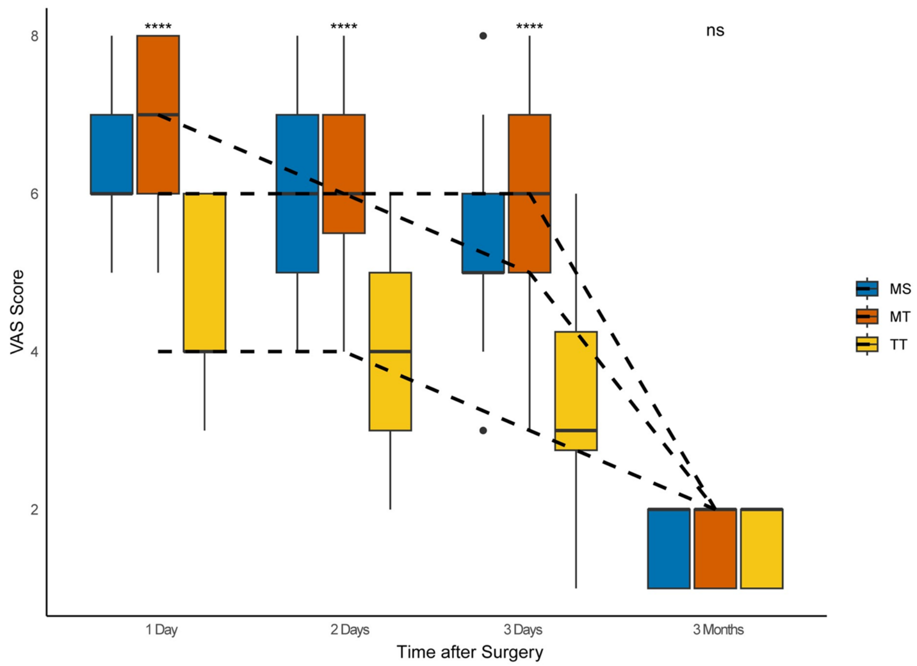

Figure 3. Postoperative Pain Trajectories by Surgical Approach. Box plots represent the distribution of VAS pain scores at 1 day, 2 days, 3 days, and 3 months post-surgery for MS (blue), MT (orange), and TT (yellow) groups. Asterisks denote statistically significant differences between time points within each group (****$p<0.0001$), while 'ns' indicates no significant difference at 3 months. The dashed lines connect the median values to illustrate the trend over time for each surgical approach.

port approaches. This additional port can provide greater flexibility in manipulation and improved visualization of the surgical area. While it involves an extra incision, this approach may enhance the convenience and safety of the surgical procedure. A "cardiocerebral event" in our study is defined as the occurrence of stroke, transient ischemic attack (TIA), and postoperative delirium. The inclusion of postoperative delirium contributes to the overall higher percentage. However, the actual stroke incidence was low, aligning with the expected safety profile of AVR surgery in middle-aged patients. Overall, both techniques aim to achieve the same surgical outcomes

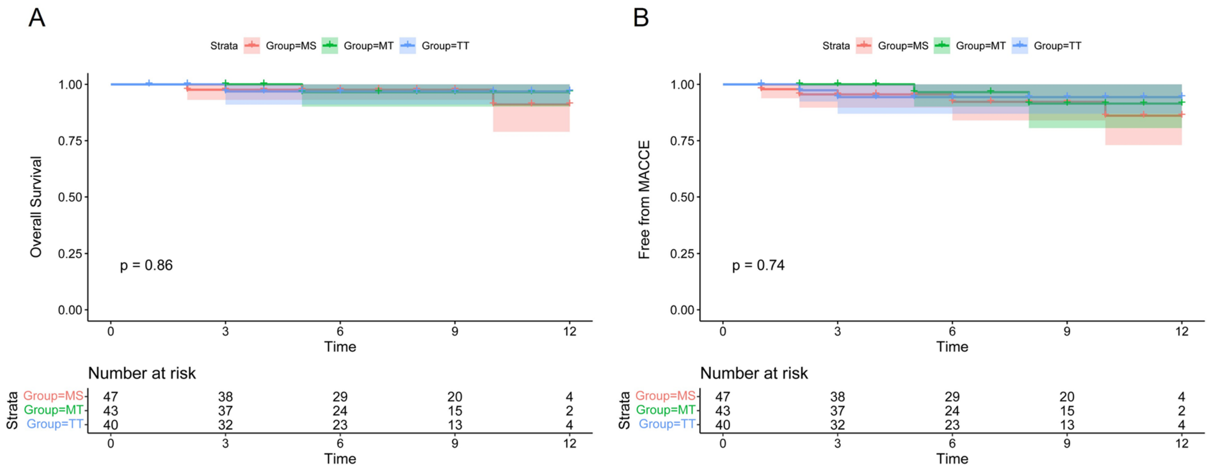

Figure 4. Kaplan–Meier Survival and Freedom from MACCE Curves. A the survival probability over time for patients undergoing AVR through three different surgical approaches. B the probability of remaining free from MACCE for the same groups over time. MACCE, Major Adverse Cardiac and Cerebrovascular Events. Central Picture Postoperative Pain Trajectories by Surgical Approach.

as traditional open-heart surgery but with smaller incisions to minimize trauma and speed up patient recovery. The choice between a two-port or three-port approach generally depends on the specific circumstances of the patient and the surgeon's preference for surgical access[13].

The study presents insightful comparisons between three surgical approaches for AVR, yet it is important to consider its limitations for a comprehensive understanding. The small sample size, while necessary for a focused initial analysis, may not capture the full variability seen in the general population, potentially affecting the robustness and generalizability of the findings. As a retrospective study, it is also subject to the constraints of pre-existing data, which can introduce biases that are not present in prospective studies. Furthermore, the absence of a mid-term follow-up means that the durability of these surgical interventions and their mid-term effects on patient health remain uncertain. Despite these limitations, the study provides valuable preliminary data and highlights the need for further research with larger and more diverse populations, as well as longer observation periods to truly validate the mid-term benefits and efficacy of the TT approach for AVR.

This study highlights the potential of the TT approach for AVR. Despite longer operation times, the TT approach demonstrated advantages such as shorter hospital stays and quicker postoperative pain reduction. These findings suggest that the TT approach could be a viable alternative for AVR surgery, potentially improving early postoperative recovery. Future research should focus on larger patient cohorts and extended follow-up periods to validate these findings and assess the mid-term impact of the TT approach on patient outcomes.

Methods
Patients
All surgical AVR procedures were performed by the same surgeon (SJ), ensuring consistency and minimizing variability. The surgical team is dedicated to providing minimally invasive aortic valve replacement surgery. Patients undergoing minimally invasive AVR were consecutively enrolled. The minimally invasive surgical approach evolved through three stages: MS, MT, and TT.

Inclusion Criteria: Adults aged 18 years or older with symptomatic severe aortic valve disease necessitating AVR, in accordance with the 2020 ACC/AHA guidelines. Only elective surgeries were included to maintain a consistent baseline across all groups.

Exclusion Criteria: Pre-existing conditions such as chest deformities, severe aortic calcifications, peripheral and cerebrovascular disease, obstructive lung disease, acute aortic regurgitation with cardiogenic shock, previous cardiac or thoracic surgery, hemodialysis, suspected severe lung adhesion, and chest wall irradiation. Additionally, patients requiring other concurrent cardiac procedures were excluded to accurately assess the specific impacts of the surgical approaches on AVR outcomes.

Specific Criteria for MT Surgery:

- The ascending aorta is positioned to the right (more than halfway to the right of the right sternal border) at the level of the main pulmonary artery.
- The distance between the ascending aorta and the sternum must not exceed 10 cm, and the α angle (the angle formed between the midline and the ascending aorta's inclination) should exceed 45°.
- No history of right thoracotomy

Specific Criteria for TT Surgery:

- The ascending aorta is not calcified, lacks significant atherosclerotic changes, and is not dilated (diameter less than 45 mm)
- No notable calcification in the aortic valve leaflets and annulus
- Access to peripheral cannulation achieved
- The patient is not undergoing hemodialysis, does not have suspected severe lung adhesion, and has no history of right thoracotomy

Ethics statement
The study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Chinese PLA General Hospital. All patients provided informed consent for their data to be used for research purposes. Patient confidentiality was maintained throughout the analysis, with all data being anonymized to prevent the identification of individual participants.

Surgical procedures and postsurgical treatment
TT group: The patient was placed in a left lateral position and intubated with a double-lumen endotracheal tube. The totally thoracoscopic procedure required a 2–3 cm working port and a thoracoscope port in the third intercostal space. Carbon dioxide was insufflated into the pericardial space, and peripheral cardiopulmonary bypass (CPB) was initiated via venous and femoral arterial cannulation under echocardiogram guidance. Aortic root and left ventricular venting were conducted through the working port and right upper pulmonary vein, respectively, and the Chitwood clamp was inserted through the fourth intercostal space, which later served as the chest tube exit. After opening the pericardial reflection and safely clamping, cardioplegia was administered, especially directly into the coronary ostia in cases of aortic insufficiency. A transverse aortotomy allowed for excision of the aortic valve leaflets, annular decalcification, sizing, and prosthetic valve implantation. Aortic closure, de-airing, and hemodynamic stabilization followed, after which CPB was discontinued, hemostasis achieved, heparin reversed with protamine, and cannulas removed. Postoperatively, patients received ICU care with pain management, fluid, and ventilatory support. A multimodal pain management approach was used, including NSAIDs, opioids, and regional anesthesia. The thoracoscopic AVR is depicted in Fig. 5.

MS group: The surgical access involved making a 5–6 cm skin incision from the sternomanubrial junction to the 4th intercostal space. Either a J-shaped (right-sided) or a L-shaped (left-sided) MS can be performed (given the CT-scan evaluation of the position of the aorta). Left ventricular vent is placed to the right superior pulmonary vein. Conventional central cannulation can be routinely achieved for CPB and AVR could be performed in the same manner as a standard sternotomy access.

MT group: The surgical access was achieved through a 5–6 cm incision beginning 1 cm lateral to the sternum at either the 2nd or 3rd right intercostal space. CPB is established by means of femoral cannulation. Pericardial

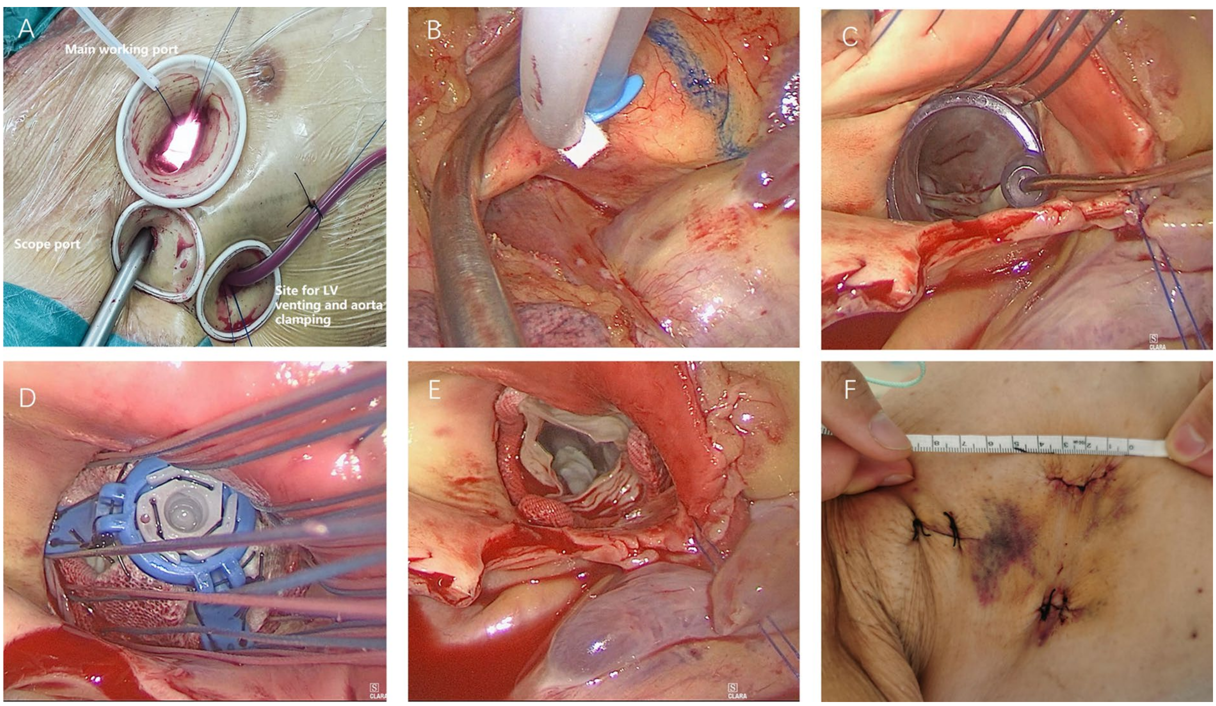

Figure 5. Operative setup of totally thoracoscope AVR. (**A**) Incisions of totally thoracoscope AVR; (**B**) After safe cross-clamping, cardioplegia was administered antegrade via aortic root vent; (**C**) Sizing the aortic annulus; (**D**) Inserting the U-sutures into the Medtronic Mosaic aortic valve prosthesis and firmly fix the prosthesis; E Adequate traction sutures at aortic wall better exposes the aortic valve; F Immediately after wound closure.

traction sutures are placed and a left ventricular vent is routinely placed. Aortic cross-clamping is achieved using a Chitwood Debakey aortic clamp positioned at the 3rd intercostal space on the anterior-mid axillary line. To facilitate suturing and valve implantation, long-shafted minimally invasive instruments are preferred. A thoracoscope port lateral to the incision helps to enhance visualization if needed.

Data collection

In this retrospective study, data collection encompassed demographic information (age, BMI), clinical parameters (LVEF, LVD), and gender distribution to characterize the patient population undergoing AVR through TT, MT, or MS approaches. Operational data such as the duration of surgery, CPB and ACC times were meticulously recorded, alongside postoperative complications including respiratory issues and cardiocerebral events. Pain levels were quantified using Visual Analog Scale (VAS) scores at various postoperative intervals, while cardiac biomarker levels, including Creatine Kinase MB (CK-MB) and Cardiac Troponin T (cTnT) were monitored for the first three days after surgery. Data on the length of hospital and ICU stays were also included to evaluate the recovery trajectory, with all patient data anonymized and managed in compliance with ethical standards.

Follow-up

Our study's follow-up entailed structured interviews at set intervals post-surgery to track patient outcomes, specifically at 3 months and 1 year, focusing on major adverse cardiac and cerebrovascular events (MACCE) and mortality rates. MACCE included complications like cardiac death, myocardial infarction, stroke, and prosthetic valve deterioration. To safeguard data integrity, we stored all information in a secure database with a quality control system, ensuring data accuracy and completeness.

Statistical analysis

Statistical analyses were performed with R software (version 4.3.2). Categorical data were summarized with counts and percentages, while continuous data were described using medians with interquartile ranges or means with standard deviations. Chi-square or Fisher's exact tests and one-way ANOVA or Kruskal–Wallis tests compared baseline characteristics across groups. Operative and in-hospital outcomes, such as duration of hospital stay and surgery, CPB, and ACC times, were analyzed based on data distribution using corresponding statistical tests.

Postoperative pain was assessed via VAS scores at different times using repeated measures ANOVA or the Friedman test, depending on data normality, to evaluate pain trends postoperatively. Mid-term outcomes like survival and MACCE incidence were assessed using Kaplan–Meier curves and log-rank tests for group survival probabilities. Statistical significance was determined by a P value of less than 0.05.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. Access to the data may be subject to restrictions due to privacy or ethical policies. Interested researchers are encouraged to contact the author directly to discuss data availability and terms of access.

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Author contributions

Author H.S. and L.L. contributed to the conception and design of the study, acquisition of data, and analysis and interpretation of data. Author N.C. played a role in drafting the article and revising it critically for important intellectual content. Author D.L. and S.D. provided assistance in data collection and interpretation, and also contributed to the manuscript preparation. Author H.S. was involved in the analysis of the data and provided statistical expertise. Author L.Z. and S.L., who is also the corresponding author, oversaw the project, contributed to the study's conception and design, and provided final approval of the version to be published. All authors agreed 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.

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Competing interests
The authors declare no competing interests.

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