



Propensity-matched analysis of robotic versus sternotomy approaches for mitral valve replacement

Wenlong Yan¹ · Yangyang Wang² · Wei Wang¹ · Qingjiang Wang¹ · Xin Zheng³ · Sumin Yang¹

Received: 21 May 2023 / Accepted: 2 July 2023 / Published online: 9 July 2023
© The Author(s) 2023

Abstract

To compare early and medium-term outcomes between robotic and sternotomy approaches for mitral valve replacement (MVR). Clinical data of 1393 cases who underwent MVR between January 2014 and January 2023 were collected and stratified into robotic MVR (n = 186) and conventional sternotomy MVR (n = 1207) groups. The baseline data of the two groups of patients were corrected by the propensity score matching (PSM) method. After matching, the baseline characteristics were not significantly different between the two groups (standardized mean difference < 10%). Moreover, the rates of operative mortality (P = 0.663), permanent stroke (P = 0.914), renal failure (P = 0.758), pneumonia (P = 0.722), and reoperation (P = 0.509) were not significantly different. Operation, CPB and cross-clamp time were shorter in the sternotomy group. On the other hand, ICU stay time, post-operative LOS, intraoperative transfusion, and intraoperative blood loss were shorter or less in the robot group. Operation, CPB, and cross-clamp time in robot group were all remarkably improved with experience. Finally, all-cause mortality (P = 0.633), redo mitral valve surgery (P = 0.739), and valve-related complications (P = 0.866) in 5 years of follow-up were not different between the two groups. Robotic MVR is safe, feasible, and reproducible for carefully selected patients with good operative outcomes and medium-term clinical outcomes.

Keywords Mitral valve replacement · Robot · Sternotomy · Propensity score matching

Introduction

Mitral valve (MV) disease is one of the commonest valvular cardiac disorders worldwide [1]. Common types of mitral valve disease in adults include degenerative, rheumatic, ischemic and infectious processes. The treatment of these different mitral valve diseases depends on the cause, pathophysiology, and natural history of each disease. According to current guidelines [2, 3], mitral valve repair (MVP) and percutaneous mitral balloon commissurotomy (PMBC) are

the preferred treatment for mitral regurgitation and mitral stenosis. However, mitral valve replacement (MVR) remains an important treatment option for patients not eligible for MVR or PMBC, especially in rheumatic MV cases.

With the decrease in operative mortality and postoperative complications, patients put forward new and higher requirements for mitral valve surgery. For example, the sternotomy is often associated with long recovery times, poor cosmetic results, and severe deep sternal wound infection. To avoid some drawbacks of sternotomy, the minimally invasive MV technique first appeared in the 1990s and has since gained popularity [4]. After nearly three decades of development, robotic systems now have excellent three-dimensional views, precise movements, and auxiliary equipment that can shorten the learning cycle for surgeons [5]. The feasibility and safety of robotic MVP has been proved in many studies [6–9], with the primary goal of improving cosmetic results and reducing postoperative complications while maintaining the same prognosis as sternotomy surgery. However, the reports comparing robotic and sternotomy MVR are limited. Thus, the current investigation was developed to report the

Wenlong Yan and Yangyang Wang have contributed equally to this study.

✉ Sumin Yang
yangsumin@qdu.edu.cn

¹ Department of Cardiovascular Surgery, The Affiliated Hospital of Qingdao University, Qingdao, Shandong, China

² Department of Nuclear Medicine, The Affiliated Hospital of Qingdao University, Qingdao, Shandong, China

³ Surgical Operating Room, The Affiliated Hospital of Qingdao University, Qingdao, Shandong, China

early and medium-term outcomes of robotic MVR in comparison with sternotomy approach.

Patients and methods

Study population

This retrospective analysis was conducted on 1458 patients diagnosed with MV disease who underwent MVR surgery at the Affiliated Hospital of Qingdao University from January 2014 to January 2023 (Fig. 1). Patients in this study met the recommendations of 2020 ACC/AHA (United States) or 2021 ESC/EACTS (European) guidelines [2, 3]. The exclusion criteria included: patients who received emergency surgery, former heart surgery and less than 18 years old. And patients who received MVR combined with other surgery (except tricuspid repair, radiofrequency ablation and thrombectomy) were also excluded. This study included the patient who initially planned MVP and converted to MVR. The included participants were stratified into two groups, the robot and sternotomy groups based on the approach. Patients selected for robotic surgery were carefully screened, and the exclusion criteria for robotic MVR are shown in Table 1. The safety and clinical efficacy of the two surgical methods

Table 1 Exclusion criteria for robotic surgery

Severe pleural adhesions (previous right thoracotomy, thoracic trauma, pleuritis)
Severe pulmonary dysfunction
LV dysfunction
Pulmonary artery pressure > 70 mm Hg or severe RV dysfunction
LV dysfunction
Femoral artery diameter < 7 mm
Severe peripheral vascular disease
Renal disease
Significant mitral annular calcification
Kyphoscoliosis and pectus excavatum
Morbid obesity
Greater than mild aortic regurgitation or significant aortic stenosis
Coronary artery disease—requiring CABG

LV left ventricle, RV right ventricle, CABG coronary artery bypass grafting

were compared using the propensity score matching (PSM) method to decrease differences and bias that might influence the treatment selection and outcomes. The screening algorithm used for patients with MV disease is depicted in Fig. 1. This study was approved by the Institutional Review Board of the Affiliated Hospital of Qingdao University (approval number: QYFY WZLL 27718; date: March 29, 2023), and the requirement for informed consent was waived.

Surgical methods

Robotic surgery was performed with the daVinci Surgical System SI (Intuitive Surgical, Inc., Mountain View, CA, USA). After inducing general anesthesia, isolating the right lung was essential, for which a right-sided bronchial blocker or a double-lumen endotracheal tube were approached, being the commonest modalities in this context. External defibrillator pads were applied, crossing the cardiac mass, and connected before starting the procedure. Then a transesophageal echocardiography (TEE) probe, right internal jugular venous drainage cannula, and Swan-Ganz catheter were applied. Normal placement has the patient lying supine having their right thorax raised and the right arm at the side, which causes the shoulder to remain moved backwards. A 23-Fr or 21-Fr cannula (Medtronic, Minneapolis, MN, USA) is inserted into the right femoral vein, and a 15-Fr cannula (Medtronic) is inserted into the right internal jugular vein to facilitate venous drainage. Using a 20-Fr or 18-Fr cannula (Medtronic, Minneapolis, MN, USA), retrograde arterial blood flow is created via the right femoral artery. In the right 4th intercostal space, laterally to the anterior axillary line, a working port of 4–5 cm is created. In the right 2nd intercostal space, on the anterior axillary line, is where the port for the left robot arm was implanted. The port for

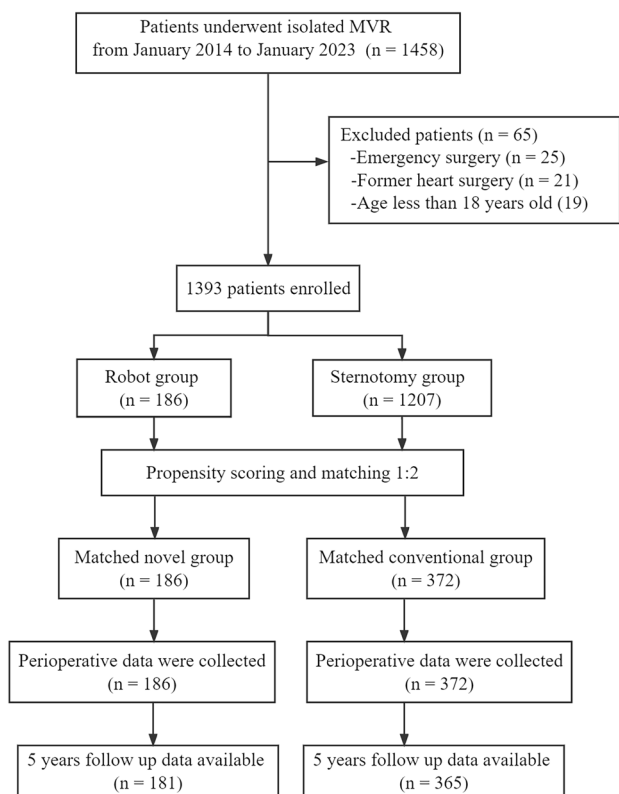


Fig. 1 Patient flow diagram

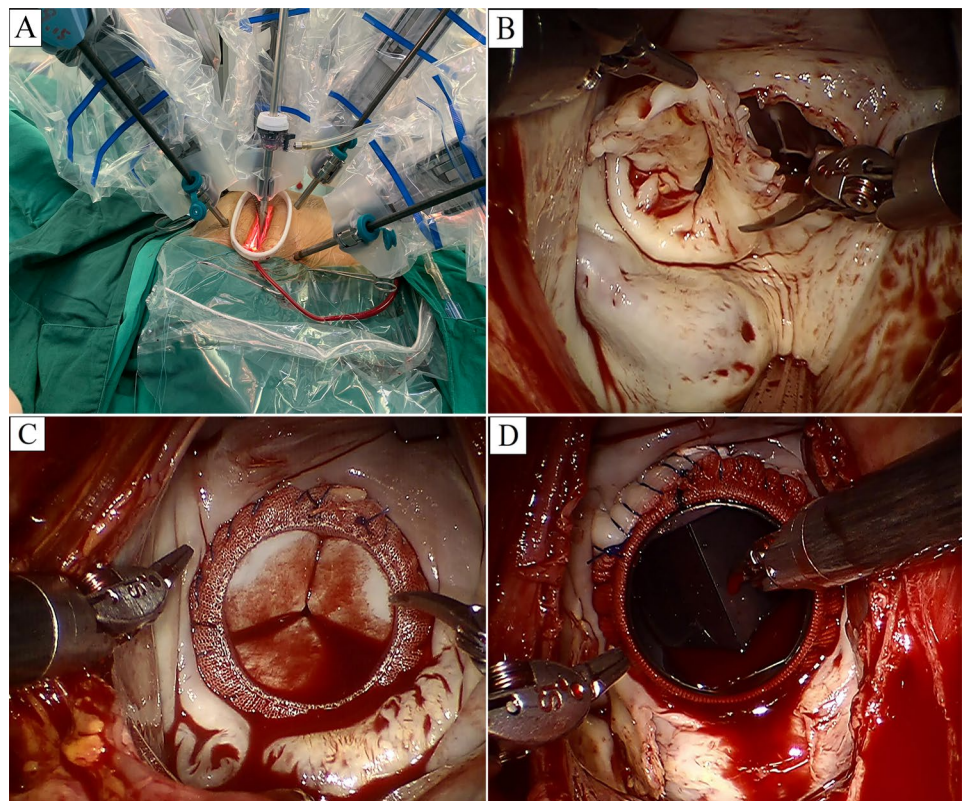
the right robot arm was situated in the right 6th intercostal space, midaxillary line. The mid-clavicular line of the right 5th intercostal space was chosen as the ideal location for the dynamic retractor arm (Fig. 2A). The Chitwood Transthoracic Aortic Cross-clamp (Scanlan International, Minneapolis, MN) was the choice when cross-clamping the aorta through the chest. Repeated doses of antegrade cold blood cardioplegic solution were delivered via the working port when needed. To avoid camera fogging and to remove air from the hemithorax, warm CO₂ was continually insufflated into the operating area. As seen in Fig. 2B, the posterior leaflets were retained wherever feasible during the removal of the sick mitral valve. An incision was made in the left atrium perpendicular to the atrial septum. A dynamic atrial retractor was used to reveal the mitral valve. In order to have a clean surgical site, a flexible drainage catheter was inserted into the left superior pulmonary vein. Carbo-Medics mechanical valve (Sulzer Carbomedics, Austin, TX), St. Jude Medical Regent Mechanical Heart Valve (St. Paul, MN), and Carpentier-Edwards PERIMOUNT Plus Pericardial Bioprosthesis (Edwards Lifesciences, Irving, CA) were the replacement valves (Fig. 2C, D). After the sutures were threaded through the incision and inserted in the prosthesis sewing ring outside of the chest, the prosthesis was dropped into place and the knots were tied with the help of a knot pusher. De-airing the heart, closing the atrium, and removing cardiopulmonary bypass allowed for a thorough TEE

examination. When the right atrium must be opened for a concomitant tricuspid valve repair, caval tapes are applied to prevent air entrainment.

Statistical analysis

Student's t-test was used to examine normally scattered continuous data represented as mean standard deviation (SD). Median and interquartile ranges were calculated for continuous data with no normal distribution, and the Mann–Whitney U test was used for statistical significance. Furthermore, Fisher's exact test or Pearson's χ^2 test was used to examine data using categorical variables, which were reported as percentages. The data was analyzed considering all patients who were eligible to participate. To minimize bias between the two groups, PSM was calculated using a logistic regression based on eighteen factors: age, male, body mass index (BMI), hypertension, diabetes mellitus, peripheral arterial disease (PAD), renal disease, chronic lung disease, cerebrovascular disease, New York Heart Association (NYHA) class, left ventricular ejection fraction (LVEF), left ventricular end-diastolic diameter (LVEDD), left atrial anterior and posterior diameter, systolic pulmonary artery pressure (SPAP), cardiothoracic ratio (CTR), Etiology, concomitant surgery, Society of Thoracic Surgeons predicted risk of mortality (STS PROM). Standardized mean differences (SMD) were used

Fig. 2 Robotic mitral valve replacement. **A** Four robotic arms are docked to a patient's right chest. From left to right: left instrument arm, camera arm, dynamic retractor arm, and right instrument arm. **B** The diseased mitral valve is excised. **C** Robotically seated bioprosthetic valve. **D** Robotically seated mechanical valve



to assess the equilibrium after matching, and PSM was carried out using the closest neighbor approach with a 0.2 caliper and a 1:2 ratio. Operation time, CPB time and cross-clamp time were analyzed using a non-linear regression model (r^2) to assess learning period effects. The hazard ratio (HR) of clinical outcomes was determined using the Cox proportional hazard model, and the time-to-event Kaplan–Meier curve was used to show the progression of all-cause mortality, subsequent mitral valve surgery, and valve-related comorbidities. The PSM analysis was conducted using R Analysis 4.2.2 (R Core Team, R Foundation for Statistical Computing, Vienna, Austria). SPSS version 23.0 (IBM, Armonk, NY, USA) was used to run other statistical analyses and generate the graphics. Statistical significance was assumed when the P value was less than 0.05.

Results

Baseline characteristics

Totally, 1458 procedures were conducted, of which 25, 21, and 19 cases were excluded being emergency, with a history of cardiac operation, and conducted with age < 18 years. Eventually, 1393 cases were included. Rheumatic MV disease was the commonest condition in this population. Patients were grouped into robot (N = 186), and sternotomy (N = 1207) groups. Different baseline characteristics are listed in Table 2. The two groups had a statistically significant difference in BMI, chronic lung disease, LVEDD, LA, and STS PROM. Furthermore, 558 cases were considered after PSM with a standardized mean difference (SMD) of < 10% for all

Table 2 Baseline characteristics before matching

	Robot group (n = 186)	Sternotomy group (n = 1207)	P value
Age (years)	61.4 ± 8.8	62.2 ± 8.3	0.225
Female	121 (65.1%)	818 (67.8%)	0.462
BMI (kg/m ²)	23.6 ± 3.1	24.4 ± 3.6	0.004
Hypertension	31 (16.7%)	207 (17.1%)	0.870
Diabetes mellitus	21 (11.3%)	149 (12.3%)	0.683
PAD	3 (1.6%)	50 (4.1%)	0.093
Renal disease	5 (2.7%)	45 (3.7%)	0.478
Chronic lung disease	8 (4.3%)	105 (8.7%)	0.041
Cerebrovascular disease	6 (3.2%)	49 (4.1%)	0.587
NYHA class			0.684
I	17 (9.1%)	97 (8.0%)	
II	97 (52.2%)	587 (48.6%)	
III	67 (36.0%)	483 (40.0%)	
IV	5 (2.7%)	40 (3.3%)	
LVEF < 50%	10 (5.4%)	106 (8.8%)	0.118
LVEDD, mm	45.7 ± 6.8	46.9 ± 6.3	0.017
LA, mm	48.3 ± 8.5	49.9 ± 8.8	0.021
SPAP	45.1 ± 13.8	45.7 ± 14.2	0.590
CTR < 0.5	102 (54.8%)	601 (49.8%)	0.200
Etiology			0.294
Rheumatic	113 (60.8%)	667 (55.3%)	
Degenerative	68 (36.6%)	489 (40.5%)	
Other	5 (2.7%)	51 (4.2%)	
Concomitant surgery			
Tricuspid repair	34 (18.3%)	264 (21.9%)	0.266
Radiofrequency ablation	38 (20.4%)	325 (26.9%)	0.060
Thrombectomy	18 (9.7%)	121 (10.0)	0.883
STS PROM (%)	4.8 ± 1.7	5.1 ± 1.6	0.018

BMI body mass index, *PAD* peripheral arterial disease, *NYHA* New York Heart Association, *LVEF* left ventricular ejection fraction, *LVEDD* left ventricular end–diastolic diameter, *LA* left atrium, *SPAP* systolic pulmonary artery pressure, *CTR* cardiothoracic ratio, *STS* Society of Thoracic Surgeons, *PROM* predicted risk of mortality

variables (Table 3). The absolute SMD before and after matching are shown in Fig. 3.

Perioperative data

In the robot group, all 186 patients underwent successful robotic MVR with bioprosthetic or mechanical valves. The function of prostheses was confirmed satisfactory by intraoperative TEE in all patients. Perioperative data before matching are presented in Table 4. Cross-clamp, CPB, and operation times were all significantly shorter in the sternotomy group, whereas ICU stay time, post-operative LOS, intraoperative transfusion, postoperative transfusion and intraoperative blood loss were significantly shorter or less in the robot group. Operative mortality before matching was significantly lower in the robot group than in the sternotomy group. Perioperative data after matching are presented in

Table 5. Operation, CPB and cross-clamp times were still shorter in the sternotomy group. ICU stay time, post-operative LOS, intraoperative transfusion and intraoperative blood loss were still shorter or less in the robot group. Operative mortality and postoperative transfusion became no difference between the two groups.

Comparison between the surgeon's early and late experience

The mean operation, CPB and cross-clamp times of robot group were 237 ± 51 min, 155 ± 42 min and 98 ± 31 min, respectively. Moreover, these mean times had a chronological significant improvement with experience ($r^2 = 0.623$, $P < 0.001$; $r^2 = 0.603$, $P < 0.001$; $r^2 = 0.631$, $P < 0.001$, respectively) (Fig. 4). The first 50 cases of robot group were defined as group 1 and the latter 136 cases of robot group

Table 3 Baseline characteristics after matching

	Robot group (n = 186)	Sternotomy group (n = 372)	P value	Absolute SMD
Age (years)	61.4 ± 8.8	61.2 ± 8.5	0.796	0.017
Female	121 (65.1%)	252 (67.7%)	0.525	0.056
BMI (kg/m ²)	23.6 ± 3.1	23.5 ± 3.3	0.731	0.042
Hypertension	31 (16.7%)	64 (17.2%)	0.873	0.036
Diabetes mellitus	21 (11.3%)	51 (13.7%)	0.422	0.076
PAD	3 (1.6%)	9 (2.4%)	0.757	0.064
Renal disease	5 (2.7%)	12 (3.2%)	0.728	0.083
Chronic lung disease	8 (4.3%)	18 (4.8%)	0.776	0.039
Cerebrovascular disease	6 (3.2%)	11 (3.0%)	0.862	0.061
NYHA class			0.963	0.035
I	17 (9.1%)	31 (8.3%)		
II	97 (52.2%)	189 (50.8%)		
III	67 (36.0%)	141 (37.9%)		
IV	5 (2.7%)	11 (3.0%)		
LVEF < 50%	10 (5.4%)	22 (5.9%)	0.797	0.024
LVEDD, mm	45.7 ± 6.8	45.4 ± 6.6	0.617	0.057
LA, mm	48.3 ± 8.5	48.7 ± 8.9	0.612	0.044
SPAP	45.1 ± 13.8	45.0 ± 13.6	0.590	0.010
CTR < 0.5	102 (54.8%)	208 (55.9%)	0.810	0.022
Etiology			0.909	0.054
Rheumatic	113 (60.8%)	219 (58.9%)		
Degenerative	68 (36.6%)	142 (38.2%)		
Other	5 (2.7%)	11 (3.0%)		
Concomitant surgery				
Tricuspid repair	34 (18.3%)	66 (17.7%)	0.876	0.014
Radiofrequency ablation	38 (20.4%)	74 (19.9%)	0.881	0.013
Thrombectomy	18 (9.7%)	40 (10.8)	0.695	0.073
STS PROM (%)	4.8 ± 1.7	4.7 ± 1.8	0.529	0.003

SMD standardized mean difference, BMI body mass index, PAD peripheral arterial disease, NYHA New York Heart Association, LVEF left ventricular ejection fraction, LVEDD left ventricular end-diastolic diameter, LA left atrium, SPAP systolic pulmonary artery pressure, CTR cardiothoracic ratio, STS Society of Thoracic Surgeons, PROM predicted risk of mortality

Fig. 3 Absolute standardized mean differences

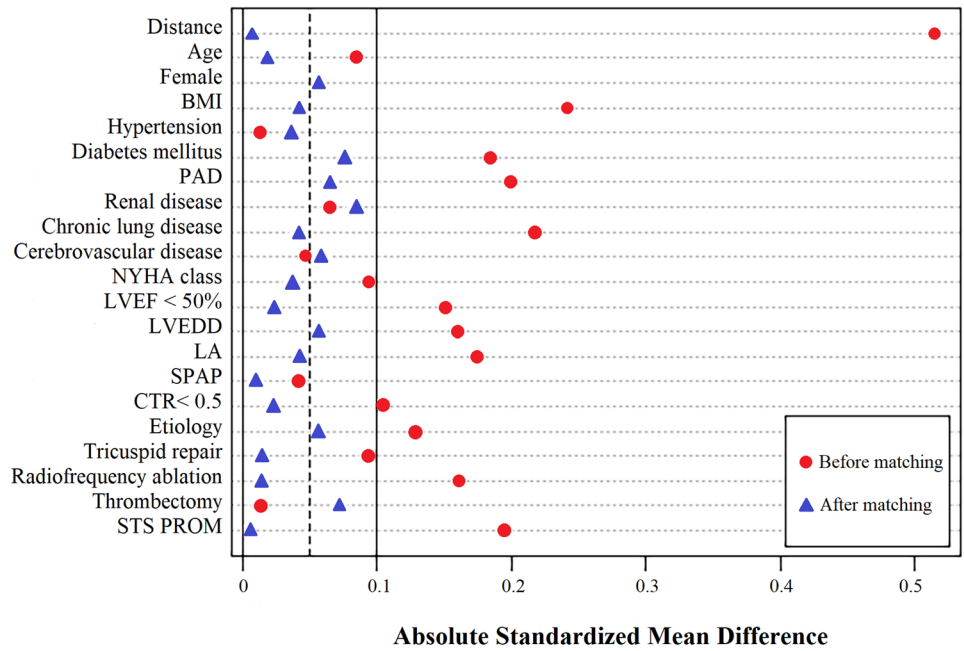


Table 4 Perioperative outcomes before matching

	Robot group (n = 186)	Sternotomy group (n = 1207)	P value
Bioprosthesis implantation	111 (59.7%)	728 (60.3%)	0.869
Operation time, min	237 ± 51	188 ± 43	<0.001
CPB time, min	155 ± 42	112 ± 25	<0.001
Cross-clamp time	98 ± 31	80 ± 21	<0.001
ICU stay time, hour	27.3 ± 7.6	34.2 ± 8.1	<0.001
Post-operative LOS, day	9.6 ± 3.3	11.2 ± 3.8	<0.001
Intraoperative transfusion, units	1.1 ± 0.8	1.8 ± 1.1	<0.001
Postoperative transfusion, units	2.3 ± 1.7	3.0 ± 1.5	<0.001
Intraoperative blood loss, mL	435 ± 188	520 ± 212	<0.001
Operative mortality	1 (0.5%)	40 (3.3%)	0.037
Reoperation	5 (2.7%)	55 (4.6%)	0.243
Wound infection	2 (1.1%)	21 (1.7%)	0.724
Permanent stroke	3 (1.6%)	36 (3.0%)	0.292
Permanent ventilation > 24 h	29 (15.6%)	175 (14.5%)	0.695
Renal failure	8 (4.3%)	57 (4.7%)	0.800
Permanent pacemaker implantation	4 (2.1%)	29 (2.4%)	0.961
Pneumonia	4 (2.2%)	22 (1.8%)	0.986
New onset atrial fibrillation	45 (24.2%)	352 (29.2%)	0.162
IABP	5 (2.7%)	49 (4.1%)	0.367
ECMO	2 (1.1%)	20 (1.7%)	0.782

CPB cardiopulmonary bypass, ICU intensive care unit, LOS length of stay, IABP intra-aortic balloon pump, ECMO extracorporeal membrane oxygenation

Table 5 Perioperative outcomes after matching

	Robot group (n = 186)	Sternotomy group (n = 372)	P value
Bioprosthesis implantation	111 (59.7%)	208 (55.9%)	0.397
Operation time, min	237 ± 51	179 ± 39	<0.001
CPB time, min	155 ± 42	106 ± 21	<0.001
Cross-clamp time	98 ± 31	78 ± 18	<0.001
ICU stay time, hour	27.3 ± 7.6	28.9 ± 7.9	0.023
Post-operative LOS, day	9.6 ± 3.3	10.4 ± 3.6	0.011
Intraoperative transfusion, units	1.1 ± 0.8	1.3 ± 0.7	0.003
Postoperative transfusion, units	2.3 ± 1.7	2.5 ± 1.6	0.173
Intraoperative blood loss, mL	435 ± 188	478 ± 191	0.012
Operative mortality	1 (0.5%)	5 (1.3%)	0.663
Reoperation	5 (2.7%)	14 (3.8%)	0.509
Wound infection	2 (1.1%)	6 (1.6%)	0.900
Permanent stroke	3 (1.6%)	8 (2.2%)	0.914
Permanent ventilation > 24 h	29 (15.6%)	49 (13.2%)	0.437
Renal failure	8 (4.3%)	14 (3.8%)	0.758
Permanent pacemaker implantation	4 (2.1%)	9 (2.4%)	0.921
Pneumonia	4 (2.2%)	5 (1.3%)	0.722
New onset atrial fibrillation	45 (24.2%)	97 (26.1%)	0.631
IABP	5 (2.7%)	11 (3.0%)	0.858
ECMO	2 (1.1%)	3 (0.8%)	0.874

CPB cardiopulmonary bypass, ICU intensive care unit, LOS length of stay, IABP intra-aortic balloon pump, ECMO extracorporeal membrane oxygenation

were defined as group 2. Compared with group 1, operation time, CPB time, cross-clamp time, post-operative LOS, intraoperative transfusion and intraoperative blood loss were statistically significantly shorter or less in group 2 (Fig. 5).

Medium-term clinical outcomes

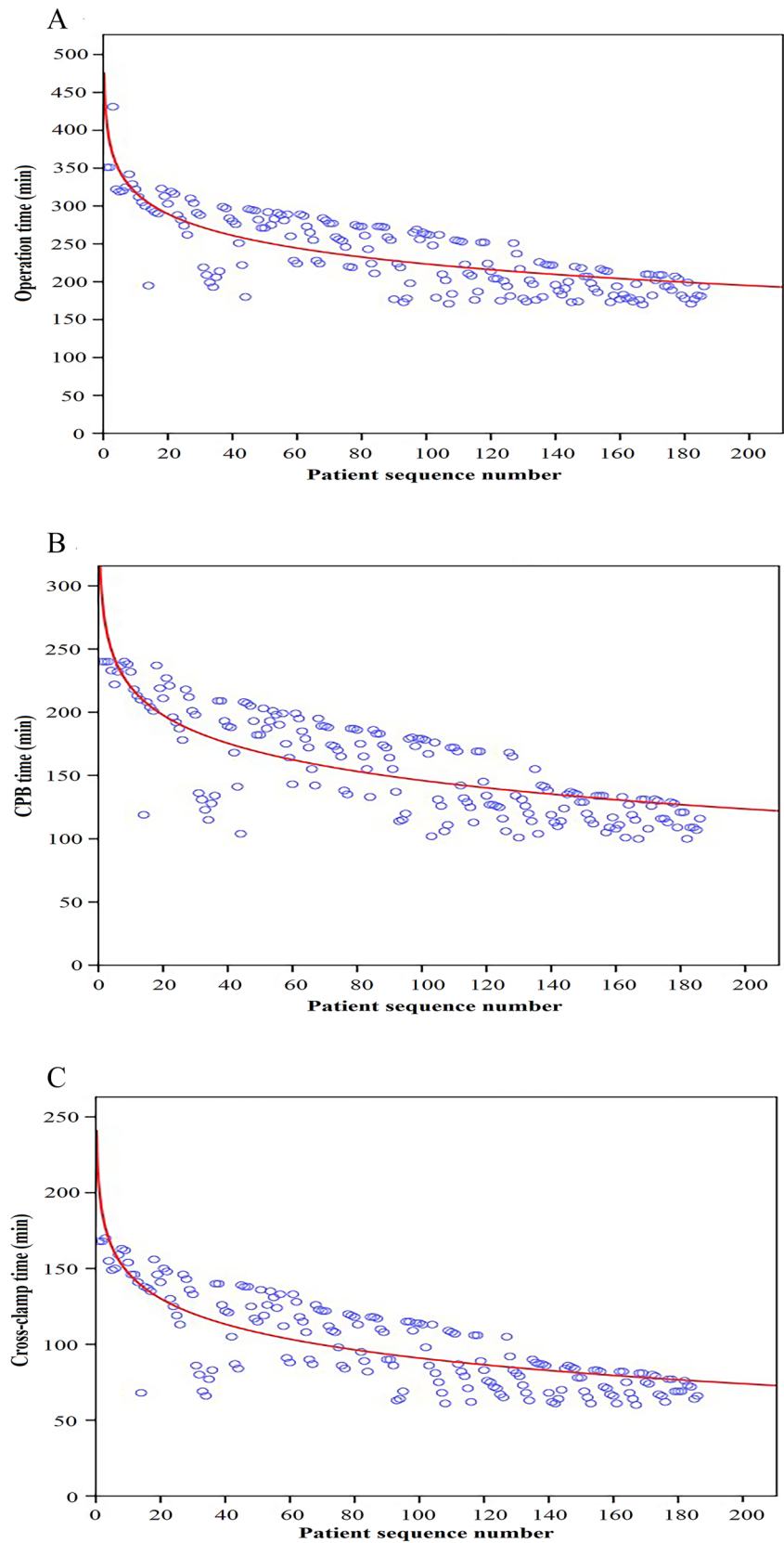
Telephonic and outpatient follow-up appointments were set-up to obtain the clinical data of our population (Tables 6 and 7 and Fig. 6). A total of 546 cases (98%) after matching were successfully followed up, which included 181 cases (97%) in the robot group and 365 cases (98%) in the sternotomy group. All-cause mortality (HR 0.831, 95% CI 0.388–1.777, $P=0.633$), redo mitral valve surgery (HR 0.836, 95% CI 0.290–2.409, $P=0.739$) and valve-related complications (HR 0.950, 95% CI 0.526–1.717, $P=0.866$) were similar between both groups. After matching, 5 patients underwent redo mitral valve surgery at 5-year follow up in the robot group. The reasons were paravalvular leak ($n=1$), regurgitation or stenosis ($n=2$), endocarditis ($n=2$). And 12 patients underwent redo mitral valve surgery at 5-year follow up in the sternotomy group. The reasons were paravalvular leak ($n=3$), regurgitation or stenosis ($n=2$), endocarditis ($n=3$), thrombosis ($n=3$) and stuck valve ($n=1$).

Discussion

In the current propensity score matched study, it was found that the robot group had prolonged procedural times but shorter ICU stay time and post-operative LOS than the sternotomy group. Moreover, the rate of perioperative and medium-term clinical complications was similar between the robot and sternotomy groups. During follow-up, all-cause mortality, redo mitral valve surgery and valve-related complications were similar between the two groups. We also observed a statistically significant reduction in procedure-related times on the learning curve in the robot group.

For severe mitral valve disease, surgery is the recommended treatment. Mitral valve repair is the preferred option. When repair is not available, biological or mechanical mitral valve replacement can be performed. Pettinari et al. [10] have reported a resurgence of interest in robotic mitral valve surgery, which is becoming more mature due to technological advances. Mounting publications demonstrate a remarkable improvement in pain intensity and recovery times correlated with robotic mitral valve surgery. Gillinov et al. [11]. analyzed the outcomes of 1,000 robotic mitral valve surgeries at their center, they found that the robotic mitral valve surgery group had a higher likelihood of valve

Fig. 4 The learning curve of robotic mitral valve replacement. **A** Operation time: y (min) = $412.52x^{-41.04}$; $r^2 = 0.623$; $P < 0.001$. **B** CPB time: y (min) = $293.96x^{-32.13}$; $r^2 = 0.603$; $P < 0.001$. **C** Cross-clamp time: y (min) = $203.26x^{-24.39}$; $r^2 = 0.631$; $P < 0.001$. *CPB* cardiopulmonary bypass



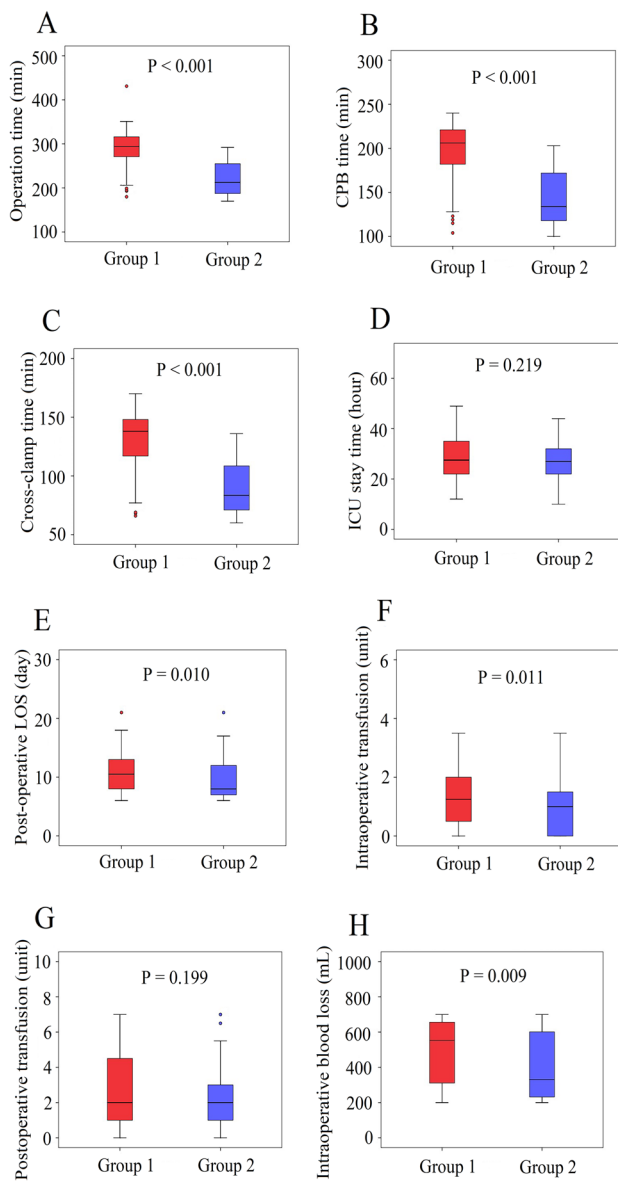


Fig. 5 Comparison between the surgeon’s early and late experience of robotic MVR. **A** Operation time. **B** CPB time. **C** Cross clamp time. **D** ICU stay time. **E** Post-operative LOS. **F** Intraoperative transfusion. **G** Postoperative transfusion. **H** Intraoperative blood loss

repair and lower operative mortality and morbidity. Arghami and colleagues [12] used echocardiography for a prolonged follow-up of 843 cases having robotic mitral valve repair, and showed that absent need of reoperation and survival were 92.6% and 93% at 10 years, respectively, indicating the effectiveness and safety of this modality with favorable prolonged outcomes that are not inferior to sternotomy.

Although the effectiveness of robotic MV surgery is widely recognized, previous studies mainly focus on mitral valve repair surgery [6–8, 11–14], and few studies independently verified the effect of robotic mitral valve replacement surgery. Robotic mitral valve replacement is more demanding and complex than repair. Arranging valve sutures and implanting prostheses through a small surgical wound might be the main challenges for conducting this modality. In order to solve these two difficulties, we adjusted the working port in the surgery (Fig. 2A). An enlarged 4–5 cm working port is made in the right fourth intercostal space, lateral to the anterior axillary line. Chitwood Transthoracic Aortic Cross-clamp, cardioplegic solution and robotic camera were administered directly through the working port. This adjustment of the working port made it easier to cross-clamp the aorta, increased the range of motion of the robotic camera, and provided a better surgical view, while reducing the difficulty of valve suture. In our series, the mean operation, CPB, and cross-clamp times of robot group were 237, 155 and 98 min, respectively. This result is better than some related studies [15, 16]. One reason is the adjustment we made to the working port, another reason may be that our robotic surgery was performed by a team which including fixed surgeons, anesthesiologists and nurses. Robot heart surgery requires excellent team cooperation. Figure 4 shows our learning curve, and we observed a trend that the mean operation, CPB, and cross-clamp times all decreased with experience on the learning curve. Further, we compared the perioperative parameters of the first 50 cases and the latter 136 cases in the robot group. Compared with the first 50 cases, operation time, CPB time, cross-clamp time, post-operative LOS, intraoperative transfusion and intraoperative blood loss were statistically significantly shorter or less in

Table 6 Five-year clinical outcomes of robotic MVR vs sternotomy MVR before matching

	Robot group (n = 181)	Sternotomy group (n = 1176)	P value	HR	95% CI
All-cause mortality	10 (5.5%)	99 (8.4%)	0.182	0.636	0.326–1.243
Redo mitral valve surgery	5 (2.8%)	60 (5.1%)	0.170	0.528	0.209–1.334
Valve-related complications	18 (9.9%)	137 (11.6%)	0.502	0.837	0.499–1.406
Bleeding events	9 (5.0%)	66 (5.6%)	0.726	0.880	0.431–1.798
Thromboembolic events	8 (4.4%)	53 (4.5%)	0.958	0.980	0.458–2.096
Infective endocarditis	2 (1.1%)	21 (1.8%)	0.725	0.615	0.143–2.643

Table 7 Five-year clinical outcomes of robotic MVR vs sternotomy MVR after matching

	Robot group (n = 181)	Sternotomy group (n = 365)	P value	HR	95% CI
All-cause mortality	10 (5.4%)	24 (6.5%)	0.633	0.831	0.388–1.777
Redo mitral valve surgery	5 (2.7%)	12 (3.2%)	0.739	0.836	0.290–2.409
Valve-related complications	18 (9.7%)	38 (10.2%)	0.866	0.950	0.526–1.717
Bleeding events	9 (4.8%)	20 (5.4%)	0.804	0.903	0.402–2.024
Thromboembolic events	8 (4.3%)	14 (3.8%)	0.744	1.159	0.477–2.816
Infective endocarditis	2 (1.1%)	5 (1.3%)	1.000	0.804	0.155–4.187

the latter 136 cases. Optimal outcomes can be attained with robotic MVR, as shown by our experience, but only after a significant learning curve and with a competent robotic crew.

Differences between the two groups have been accounted for using robust statistical approaches, and there is a satisfactory match for all measurable confounders (Fig. 3). To reflect real-world conditions, mitral combined with tricuspid repair, radiofrequency ablation, and thrombectomy were included in this study and included as matching factors in Tables 2 and 3. The operating death rate in our group is significantly reduced more than the predicted mortality based on STS PROM, indicating good operative results. Within propensity matched cohorts, although operation, CPB, and cross-clamp times were still longer in the robot group than the thoracotomy group, there was no difference in operative mortality, permanent stroke, renal failure and other complications. Furthermore, ICU stay time and post-operative LOS were statistically significantly shorter in the robot group. There are some complications that are inherent in perfusion and ventilation methods used for robotic surgery [5, 9, 17, 18]. Possible major complications related to retrograde cardiopulmonary perfusion modalities include unilateral pulmonary edema and pneumonia, prolonged ventilation, and stroke. However, in our cohort, no differences in these complications were found between the two groups either before or after matching. We hypothesize that the excellent operative outcomes in our cohort are due to the strict screening criteria before surgery. The objective of robotic MVR is

to reduce patient recovery time, improve incision-related complications, improving cosmesis and operative outcomes. The anticipated favorable outcomes should not outweigh the medium-term or longer-term surgical outcomes. The current findings are supported by similar investigations in the literature [19, 20] indicating the similarity between both modalities regarding medium-term clinical outcomes including all-cause mortality, redo mitral valve surgery and valve-related complications.

There are some limitations with this study. First, although PSM was done, confounding differences between the two treatment groups could not be completely ruled out due to the nature of the retrospective study. Second, only cases with irreparable MV disease had valve replacement surgeries, decreasing our sample size. Third, although the robot group was performed by the same team, the thoracotomy group was performed by multiple teams, so there may be a potential surgeon bias.

In conclusion, robotic MVR is safe, feasible and reproducible with good operative outcomes and medium-term clinical outcomes. Robotic MVR was associated with longer operation, CPB and cross-clamp times. Whereas ICU stay time, post-operative LOS, intraoperative transfusion and intraoperative blood loss were shorter or less in the robot group. And operation, CPB and cross-clamp times can all improve remarkably with experience. Cases requiring MVR should be aware about the potential to receive a robotic surgery.

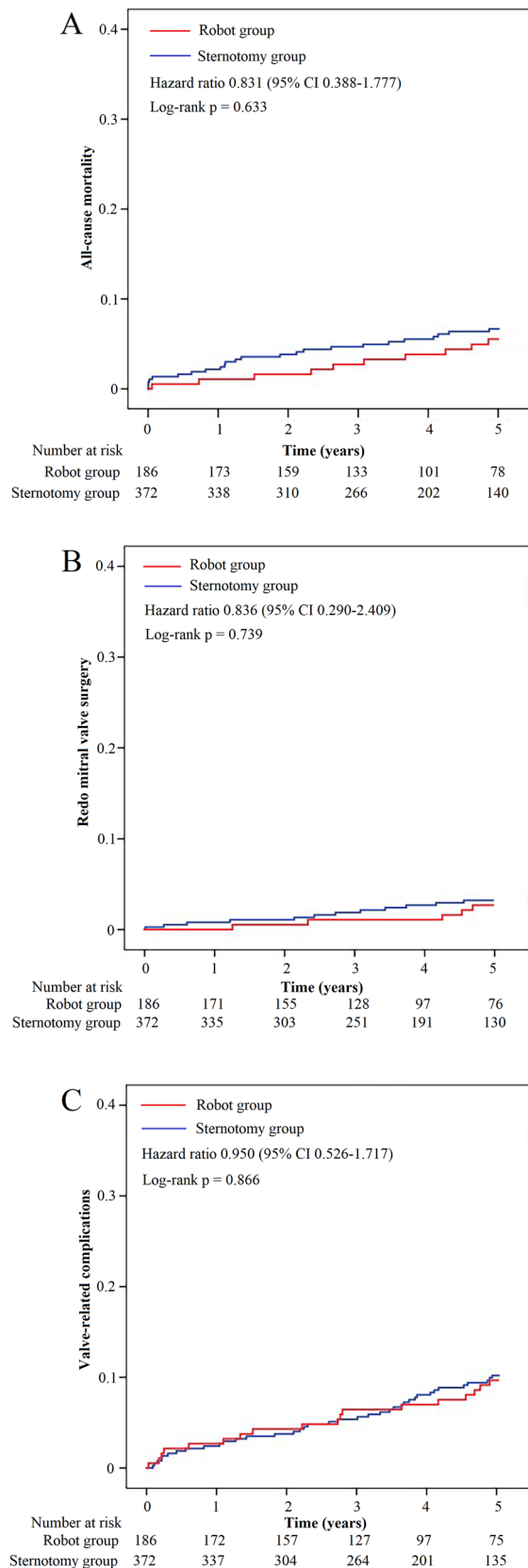


Fig. 6 Time-to-event curves for clinical outcomes after matching. **A** All-cause mortality. **B** Redo mitral valve surgery. **C** Valve-related complications

Author contributions SY: senior author, supervising consultant; WY: data collection, writing up; YW: data analysis, writing up; WW: writing up. Others involved in data collection.

Funding No funds, grants, or other support was received.

Data availability Data available upon request.

Declarations

Conflict of interest The authors declare that they have no financial interests.

Ethical approval The protocol of the study was reviewed and approved by the institutional review board of The Affiliated Hospital of Qingdao University (approval number: QYFY WZLL 27718; date: March 29, 2023).

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Nkomo VT, Gardin JM, Skelton TN et al (2006) Burden of valvular heart diseases: a population-based study. *Lancet* 368(9540):1005–1011
2. Vahanian A, Beyersdorf F, Praz F et al (2022) 2021 ESC/EACTS Guidelines for the management of valvular heart disease. *Eur Heart J* 43(7):561–632
3. Writing Committee M, Otto CM, Nishimura RA et al (2021) 2020 ACC/AHA guideline for the management of patients with valvular heart disease: executive summary: a report of the American college of cardiology/American heart association joint committee on clinical practice guidelines. *J Am Coll Cardiol* 77(4):450–500
4. Doenst T, Diab M, Sponholz C et al (2017) The opportunities and limitations of minimally invasive cardiac surgery. *Dtsch Arztebl Int* 114(46):777–784
5. Hemli JM, Patel NC (2020) Robotic cardiac surgery. *Surg Clin North Am* 100(2):219–236
6. Hawkins RB, Mehaffey JH, Mullen MG et al (2018) A propensity matched analysis of robotic, minimally invasive, and conventional mitral valve surgery. *Heart* 104(23):1970–1975
7. Kesavuori R, Raivio P, Jokinen JJ et al (2018) Early experience with robotic mitral valve repair with intra-aortic occlusion. *J Thorac Cardiovasc Surg* 155(4):1463–1471
8. Grant SW, Hickey GL, Modi P et al (2019) Propensity-matched analysis of minimally invasive approach versus sternotomy for mitral valve surgery. *Heart* 105(10):783–789
9. Williams ML, Hwang B, Huang L et al (2022) Robotic versus conventional sternotomy mitral valve surgery: a systematic review and meta-analysis. *Ann Cardiothorac Surg* 11(5):490–503

10. Pettinari M, Navarra E, Noirhomme P et al (2017) The state of robotic cardiac surgery in Europe. *Ann Cardiothorac Surg* 6(1):1–8
11. Gillinov AM, Mihaljevic T, Javadikasgari H et al (2018) Early results of robotically assisted mitral valve surgery: analysis of the first 1000 cases. *J Thorac Cardiovasc Surg.* 155(1):82-91 e2
12. Arghami A, Jahanian S, Daly RC et al (2022) Robotic mitral valve repair: a decade of experience with echocardiographic follow-up. *Ann Thorac Surg* 114(5):1587–1595
13. Murphy DA, Moss E, Binongo J et al (2015) The expanding role of endoscopic robotics in mitral valve surgery: 1,257 consecutive procedures. *Ann Thorac Surg.* 100(5):1675–1681 (**Discussion 81-82**)
14. Suri RM, Taggarse A, Burkhart HM et al (2015) Robotic mitral valve repair for simple and complex degenerative disease: mid-term clinical and echocardiographic quality outcomes. *Circulation* 132(21):1961–1968
15. Kuo CC, Chang HH, Hsing CH et al (2018) Robotic mitral valve replacements with bioprosthetic valves in 52 patients: experience from a tertiary referral hospital. *Eur J Cardiothorac Surg* 54(5):853–859
16. Gao C, Yang M, Xiao C et al (2012) Robotically assisted mitral valve replacement. *J Thorac Cardiovasc Surg* 143(4 Suppl):S64–S67
17. Moss E, Halkos ME, Binongo JN et al (2017) Prevention of unilateral pulmonary edema complicating robotic mitral valve operations. *Ann Thorac Surg* 103(1):98–104
18. Cerny S, Oosterlinck W, Onan B et al (2021) Robotic cardiac surgery in Europe: status 2020. *Front Cardiovasc Med* 8:827515
19. Sicim H, Kadan M, Erol G et al (2021) Comparison of postoperative outcomes between robotic mitral valve replacement and conventional mitral valve replacement. *J Card Surg* 36(4):1411–1418
20. Zhao H, Zhang H, Yang M et al (2020) Comparison of quality of life and long-term outcomes following mitral valve replacement through robotically assisted versus median sternotomy approach. *Nan Fang Yi Ke Da Xue Xue Bao* 40(11):1557–1563

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.