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Modified robotic atrial septal defect repair on beating heart: a nine-year single-centre experience with learning-curve analysis and comparison with thoracoscopy

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Abstract

Objective: To evaluate a modified robot-assisted technique for atrial septal defect (ASD) repair on beating heart and to compare perioperative outcomes with thoracoscopic repair.

Methods: 198 patients with ASD underwent modified ASD repair using the Da Vinci robotic surgical system on beating heart in the Department of Cardiovascular Surgery of the First Affiliated Hospital with Nanjing Medical University. Cumulative sum (CUSUM) analysis was used to build learning curves for operation time and cardiopulmonary bypass (CPB) time. Patients operated after both curves had plateaued formed the robotic group (n = 117); 113 patients treated thoracoscopically during the same period served as the comparison group.

Results: The learning curves for operation time and CPB time were 81 cases and 66 cases respectively. ASD diameter and pulmonary artery systolic pressure were higher in the robotic group, which also contained seven patients with partial anomalous pulmonary venous connection (PAPVC) and one with anomalous drainage of the inferior vena cava. CPB time was shorter in the robotic group. Operation time, mechanical ventilation time, intensive care unit stay, postoperative hospital stay and 24-hour chest drainage did not differ. Echocardiography at 3, 30 and 90 days and at one year showed no residual shunt or tricuspid regurgitation in either group.

Conclusions: The modified robot-assisted technique for beating-heart ASD repair is safe and reproducible. Once the learning curve is complete, CPB time is shorter than with thoracoscopy despite greater anatomical complexity, and the technique offers a valid minimally invasive option for defects that are unsuitable for device closure.

Keywords: Atrial septal defect; Robotic surgery; Beating heart; Cardiopulmonary bypass; Learning curve

1 Introduction

Atrial septal defect (ASD) is among the most common congenital cardiac malformations seen in adults. A persistent left-to-right shunt imposes volume load on the right heart and, if the defect is left untreated, exposes patients to atrial arrhythmia, pulmonary hypertension and right ventricular failure. Transcatheter device closure is now first-line treatment for most secundum defects because it avoids cardiopulmonary bypass (CPB) and shortens recovery.[1] The technique has boundaries, however. Large defects, defects with deficient rims, and defects lying close to the caval veins or the coronary sinus are seldom amenable to device closure,[1, 2] and device erosion or thromboembolic events may appear years later.[3] Surgical repair therefore remains necessary for a substantial proportion of patients.[4]

Totally thoracoscopic repair is an established alternative to median sternotomy. It gives a wide view of the right atrium, limits postoperative pain and leaves a small, well-hidden scar, and several centres have reported low morbidity and satisfactory early results.[5-7] The platform nevertheless has intrinsic constraints: two-dimensional imaging, rigid instruments with four degrees of freedom, and limited angulation inside a small atrial chamber. Fine suturing therefore becomes difficult, particularly along the inferior margin of a large defect or near the superior vena cava in patients with partial anomalous pulmonary venous connection (PAPVC).[8, 9]

Robot-assisted systems were introduced to overcome these constraints. Wristed instruments restore dexterity, magnified three-dimensional vision improves spatial judgement, and tremor filtering stabilises fine movements.[10, 11] Robotic ASD repair has proved safe and feasible at specialised centres,[12, 13] and Bonaros and colleagues documented a measurable learning curve for totally endoscopic robotic ASD repair.[14] Comparative evidence against thoracoscopy nevertheless remains limited.

We modified the robotic procedure by borrowing steps from our thoracoscopic practice. A dedicated atrial retractor is replaced by traction sutures that retract the right atrium and pericardium, and two large needle drivers are sufficient; a third robotic arm is not required. This report summarises nine years of experience with the modified

technique for ASD repair on the beating heart. Cumulative sum (CUSUM) analysis was used to define learning curves for operation time and CPB time, and outcomes after both curves had plateaued were compared with those of a contemporaneous thoracoscopic cohort.

2 Methods

2.1 Patients and study design

We retrospectively reviewed consecutive patients with ASD who underwent modified robot-assisted ASD repair on the beating heart at the Department of Cardiovascular Surgery, the First Affiliated Hospital with Nanjing Medical University, between December 2016 and September 2025. All procedures used the da Vinci Si or Xi system (Intuitive Surgical, Sunnyvale, CA, USA). CUSUM curves for CPB time and operation time were constructed across the whole robotic series; once both had reached a stable plateau, subsequent patients were enrolled in the robotic group. Patients who underwent thoracoscopic beating-heart ASD repair through a three-port approach during the same interval formed the comparison group. Patients in whom transcatheter closure was suitable were not offered surgery.

The study was approved by the institutional review board of the First Affiliated Hospital with Nanjing Medical University (No. 2018-SR-249), and written informed consent was obtained from all patients for publication of their data and accompanying images.

Exclusion criteria for the robotic beating-heart approach were: body weight <15 kg or body mass index >35 kg/m²; severe thoracic disease or poor pulmonary function making single-lung ventilation unsafe (preoperative arterial oxygen partial pressure <65 mmHg and/or carbon dioxide partial pressure >50 mmHg), or recent severe pulmonary infection; coronary artery disease requiring concomitant bypass grafting, or myocardial infarction within 30 days; severe intracardiac or extracardiac deformity requiring concomitant correction; and femoral arterial or venous disease precluding peripheral cannulation.

2.2 Perioperative assessment

Preoperative work-up mirrored that of totally thoracoscopic ASD repair. Peripheral vessels were assessed for CPB cannulation, and chest computed tomography was reconstructed in three dimensions to plan port placement. External defibrillation pads were applied to the anterior and right posterior chest. Patients were positioned close to the right edge of the table with the right chest elevated 20°–30°, and the right

upper limb was supported behind the torso without excessive extension. Single-lung ventilation was achieved with a bronchial blocker or a double-lumen tube.

Peripheral CPB was established by cannulating the femoral artery, femoral vein and right internal jugular vein. In one patient with a small femoral artery, bilateral femoral arterial cannulation (15F, Medtronic) was used. Transoesophageal echocardiography guided cannulation, cardiac de-airing and assessment at the end of the procedure.

Ventilation was suspended once CPB began. Resuming one-lung ventilation after CPB is often accompanied by hypoxaemia, most frequently while haemostasis is being checked. Continuous positive airway pressure, high-frequency jet ventilation or positive end-expiratory pressure to the ventilated lung can be tried; if oxygenation does not improve, the operation is paused and two-lung ventilation resumed.

2.3 Thoracoscopic technique

The thoracoscopic technique has been described previously.[5] A 1-cm incision in the fifth intercostal space at the right midaxillary line admitted the thoracoscope. Two 2-cm working incisions were then created under endoscopic guidance, one parasternal in the third intercostal space and one along the anterior axillary line, and wound protectors were inserted. The right internal mammary artery was identified and preserved, and breast tissue was avoided in women.

2.4 Robotic technique

After single-lung ventilation was established, the videoscope port was placed in the fourth intercostal space about 5–6 cm anterior to the anterior axillary line. In women the incision was made below the breast and tunnelled subcutaneously to the fourth intercostal space. The working port, 2–3 cm in diameter, was created in the same intercostal space 1–2 cm below the videoscope port, through which the pleural cavity was inspected for adhesions.

Guided by the three-dimensional computed tomography reconstruction, two 8-mm trocars were inserted for the robotic arms, one in the fifth or sixth intercostal space 2–3 cm anterior to the anterior axillary line and one in the second intercostal space 5 cm anterior to the anterior axillary line.

Drawing on our thoracoscopic experience, we simplified the procedure. The right atrium is retracted with traction sutures rather than a dedicated retractor, which reduces instrument crowding, and only two robotic large needle drivers are used; no third arm or robotic retractor is needed. The pericardium was opened about 2 cm anterior to the phrenic nerve, from the space between the ascending aorta and the superior vena cava down to the root of the inferior vena cava. Pericardial stay sutures were brought out through the intercostal space with a suture retriever, care being taken to avoid the intercostal vessels and the internal mammary artery. With the bedside surgeon assisting, both venae cavae were encircled and snared. The right atrium was opened parallel to the atrioventricular groove, and stay sutures in the atrial wall were retracted to the chest wall or anchored to the pericardium.

Inside the atrium, left-heart vent flow was adjusted to keep the operation field clear without emptying the left atrium and risking air entrainment. A bovine pericardial patch was used in every robotic repair. Suturing began at the 10 o'clock position with a 4-0 polypropylene continuous suture, the smooth surface of the patch facing the right atrium; the patch was rotated 180° when the suture reached the 3 o'clock position, and the run was continued. Because all defects in this cohort were unsuitable for device closure, margins were frequently short; particular care was therefore taken near the coronary sinus and the orifice of the inferior vena cava to place sutures in sound tissue. In patients with PAPVC, especially drainage of the right pulmonary veins into the superior vena cava, the principles were the same as for open repair. As the suture approached the inferior margin, the assistant placed the intracardiac suction between the tricuspid valve and the coronary sinus to improve exposure, while the eustachian valve was deliberately avoided. When there was doubt about the eustachian valve, the inferior vena cava snare was released briefly to confirm that it had not been incorporated. Once the suture had been run counter-clockwise from the 10 o'clock to the 6 o'clock position, coronary sinus return could no longer cross the defect, and the bedside surgeon positioned suction at the coronary sinus ostium to keep the field clear. Before the sutures were tied, the lungs were inflated by the anaesthetist to expel air from the left atrium. Tricuspid regurgitation, when present, was corrected at the same time by Kay technique or ring

annuloplasty. The atriotomy was closed with a continuous 4-0 polypropylene suture, and all incisions and puncture sites were checked for bleeding. Before separation from CPB, both lungs were ventilated with 100% oxygen; after rewarming and satisfactory blood gases had been confirmed, CPB was discontinued, heparin was reversed with protamine and the cannulas were removed. Transoesophageal echocardiography excluded a residual shunt and tricuspid regurgitation at the end of the procedure.

2.5 Data collection and follow-up

Preoperative, perioperative and follow-up data were entered prospectively into a database and reviewed retrospectively. Transthoracic echocardiography was performed at 1, 3, 6 and 12 months in the first postoperative year and annually thereafter.

2.6 Statistical analysis

The cumulative sum (CUSUM) method was applied to analyze operative time and cardiopulmonary bypass (CPB) time of the modified Da Vinci beating-heart ASD repair, enabling the construction of its learning curves. Statistical analyses were performed using SPSS version 27.0 (IBM Corp, Chicago, IL, USA). Continuous variables with a normal distribution were presented as mean ± standard deviation (SD) and compared between groups using the Student's t-test. Categorical variables were expressed as frequencies (percentages) and analyzed using Pearson's chi-square test, continuity-corrected chi-square test, or Fisher's exact test, as appropriate. A P-value < 0.05 was considered statistically significant.

3 Results

3.1 Learning curves

The CUSUM curves for CPB time and operation time (Figures 1 and 2) reached a plateau after 66 and 81 cases, respectively. Patients treated after both plateaus had been reached formed the robotic group (n = 117), which was compared with the thoracoscopic group (n = 113).

3.2 Baseline characteristics

The groups were comparable in sex, age, body surface area, body mass index, left ventricular ejection fraction and the prevalence of hypertension, diabetes mellitus, coronary artery disease and previous cerebral infarction. Mean ASD diameter was greater in the robotic group (30.10 ± 4.55 vs 28.47 ± 6.29 mm, p = 0.026), as was mean pulmonary artery systolic pressure (44.23 ± 6.90 vs 41.96 ± 8.34 mmHg, p = 0.025). Seven patients in the robotic group had PAPVC and one had anomalous drainage of the inferior vena cava into the left atrium; neither anomaly was present in the thoracoscopic group (Table 1).

3.3 Surgical data

All patients completed surgery, with no conversion to sternotomy and no intraoperative red cell transfusion. Total operation time was similar (141.02 ± 16.25 vs 144.70 ± 16.75 min, p = 0.092), whereas CPB time was shorter in the robotic group (56.27 ± 5.45 vs 59.95 ± 10.90 min, p = 0.002). Concomitant PAPVC repair was performed in the seven affected robotic patients (p = 0.014), and the patient with anomalous caval drainage underwent correction of that anomaly. Tricuspid valvuloplasty was performed in 37 robotic patients, 24 (20.51%) by the Kay technique and 13 (11.11%) with a ring, and in 24 thoracoscopic patients, 16 (14.16%) by the Kay technique and 8 (7.08%) with a ring; neither the proportion nor the distribution of techniques differed between groups. Mechanical ventilation time (5.59 ± 2.84 vs 6.17 ± 1.96 h, p = 0.075), intensive care unit stay (10.81 ± 5.08 vs 11.07 ± 3.90 h, p = 0.661), postoperative hospital stay (5.73 ± 2.73 vs 6.13 ± 1.19 days, p = 0.148) and 24-hour chest drainage (101.93 ± 57.45 vs 90.66 ± 50.88 mL, p = 0.117) were comparable (Table 2).

3.4 Complications and follow-up

No patient died within 30 days of surgery. New-onset atrial fibrillation, reoperation for bleeding, femoral cannulation complications, pulmonary hypertensive crisis, delayed extubation, re-expansion pulmonary oedema, postoperative delirium, acute kidney injury, residual shunt and wound infection occurred at similarly low rates in the two groups (Table 3). Echocardiography at 3, 30 and 90 days and at one year showed no residual shunt and no tricuspid regurgitation in either group.

4 Discussion

Minimally invasive strategies have become the dominant direction in the surgical management of ASD because they achieve anatomical closure without a sternotomy[8, 15, 16]. Robotic systems have extended what is possible through small ports, yet whether robotics offers a measurable advantage over thoracoscopy for ASD repair has not been settled by comparative data from a large single-centre cohort. We analysed 311 patients who underwent beating-heart ASD repair, 198 robotically and 113 thoracoscopically. After the robotic learning curve had been completed, CPB time was significantly shorter than with thoracoscopy, although the robotic cohort had larger defects, higher pulmonary artery pressures and a greater burden of associated anomalies.

Robotic cardiac procedures carry a learning curve that affects both efficiency and outcome, and ASD repair is no exception[9, 17]. Gao and colleagues reported progressive reductions in CPB time, aortic cross-clamp time and operation time as their robotic ASD experience accumulated,[18] and the seven-year series of Xiao and colleagues showed the same pattern for cross-clamp, operation and CPB times.[19] Bonaros and colleagues were the first to quantify the curve for totally endoscopic ASD repair.[14] In our series, operation time stabilised after 81 cases and CPB time after 66. Comparing the first and last 50 robotic cases, mean operation time fell from 152.5 ± 9.3 to 128.5 ± 14.8 min (about 24 min, 16%) and mean CPB time from 58.9 ± 4.7 to 53.8 ± 5.0 min (about 5 min, 9%). These inflection points are close to the figure of roughly 75 cases reported for robotic mitral valve repair,[20, 21] and to our own experience with totally endoscopic beating-heart ASD repair.[5] CPB time plateaued earlier than operation time, which suggests that proficiency with cannulation, snaring and separation from bypass is acquired before the whole workflow is optimised; operation time also includes access, docking and undocking, all of which depend on team coordination rather than on the console surgeon alone. A comparable pattern has been described for single-surgeon totally endoscopic ASD repair.[22] CUSUM analysis therefore provides an objective benchmark for the caseload a centre should expect to complete before a robotic ASD programme can be regarded as established.[23, 24]

Our group modified the robotic approach after several years of thoracoscopic practice. Traction sutures replace the atrial retractor, only two large needle drivers are deployed, and the third arm is left unused. Instrument crowding inside the atrium falls, arm collisions are avoided and the workflow runs more smoothly. These changes plausibly contribute to the comparatively early stabilisation of operation time in our series, although the present design cannot separate their effect from that of accumulated experience.

Baseline characteristics were generally balanced, but the robotic cohort was not identical to the thoracoscopic cohort: defects were larger, pulmonary artery pressures were higher, and seven patients had PAPVC with one additional patient showing anomalous inferior vena cava drainage. The robotic cohort therefore carried the greater anatomical complexity. That CPB time was nonetheless shorter in the robotic group is the central finding of this study. Wristed instruments with six degrees of freedom, compared with four for conventional thoracoscopic instruments, allow precise dissection and suturing in confined spaces such as the superior vena cava–right atrial junction encountered during PAPVC repair. Three-dimensional magnified vision improves spatial perception relative to two-dimensional thoracoscopy, and tremor filtering adds stability to every stitch. Anatomical repair of PAPVC through a minimally invasive approach is feasible and its midterm results are acceptable,[9] which widens the range of defects that can be managed without a sternotomy. Shorter CPB time also means less exposure to the inflammatory response of bypass and, potentially, less end-organ dysfunction.

Thirty-day mortality and major complications were comparable between groups, which supports the safety of both minimally invasive routes. It is worth placing this in context: device closure remains the least invasive option for anatomically suitable defects and compares favourably with minimally invasive surgery in pooled analyses,[4] but it is precisely the patients excluded from device therapy who require a surgical solution. For them, the choice lies between thoracoscopy and robotics.

Two practical objections to robotic surgery deserve mention. Capital and maintenance costs are high, and hospital-level economic analyses of robotic cardiac

surgery have consistently shown higher expenditure than conventional techniques.[10, 11] Preoperative set-up and docking also add time and depend on the team's familiarity with the platform. The present data suggest that these drawbacks have to be weighed against a shorter bypass run in patients with more complex anatomy; cost-effectiveness was not measured here, and the balance may differ between health systems. At follow-up to one year, echocardiography showed no residual shunt and no significant tricuspid regurgitation in either group, indicating that the early anatomical result of the modified robotic repair is durable in the short term.

5 Limitations

Several limitations should be acknowledged. First, this was a single-centre retrospective study with a modest sample size and no random allocation. Baseline anatomy differed between groups, with more complex anomalies in the robotic cohort, and residual selection bias cannot be excluded. Second, only post-learning-curve robotic cases (n = 117) entered the comparison, so perioperative data from the learning phase were not analysed and early risks may be underestimated. Third, follow-up extended to one year only, which is too short to assess residual shunt, late arrhythmia or long-term quality of life. Fourth, no formal cost or health-economic evaluation was performed. Prospective multicentre randomised studies with longer follow-up are needed to define the place of modified robotic beating-heart ASD repair.

6 Conclusions

The modified robot-assisted technique for beating-heart ASD repair is safe and reproducible, and operation time and CPB time stabilise after approximately 81 and 66 cases, respectively. Beyond the learning curve, the technique shortens CPB time relative to thoracoscopy even in patients with larger defects and more complex anatomy, while preserving the minimally invasive and cosmetic advantages of small incisions.

CRediT authorship contribution statement

HanChao Feng, Mingke Li and JinMo Kong: Conceptualization, Formal analysis, Investigation, Writing Original Draft, collect and analysis data. Yawei Dai: Supervision. YiHu Tang and YanHu Wu: Conceptualization, Writing - Review & Editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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None.

Figures

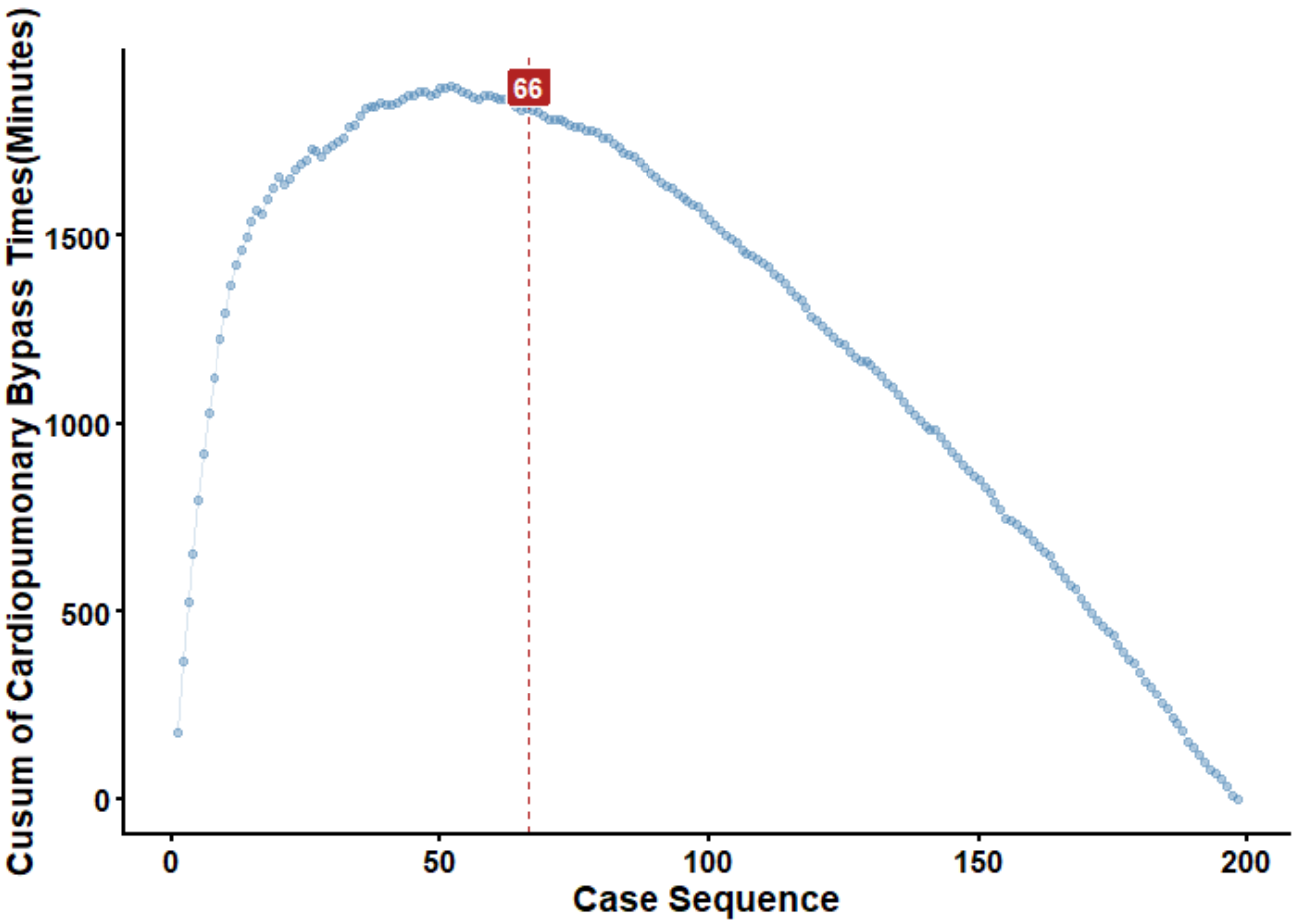


Figure 1 CUSUM learning curve for cardiopulmonary bypass time. The curve reaches a plateau after 66 cases.

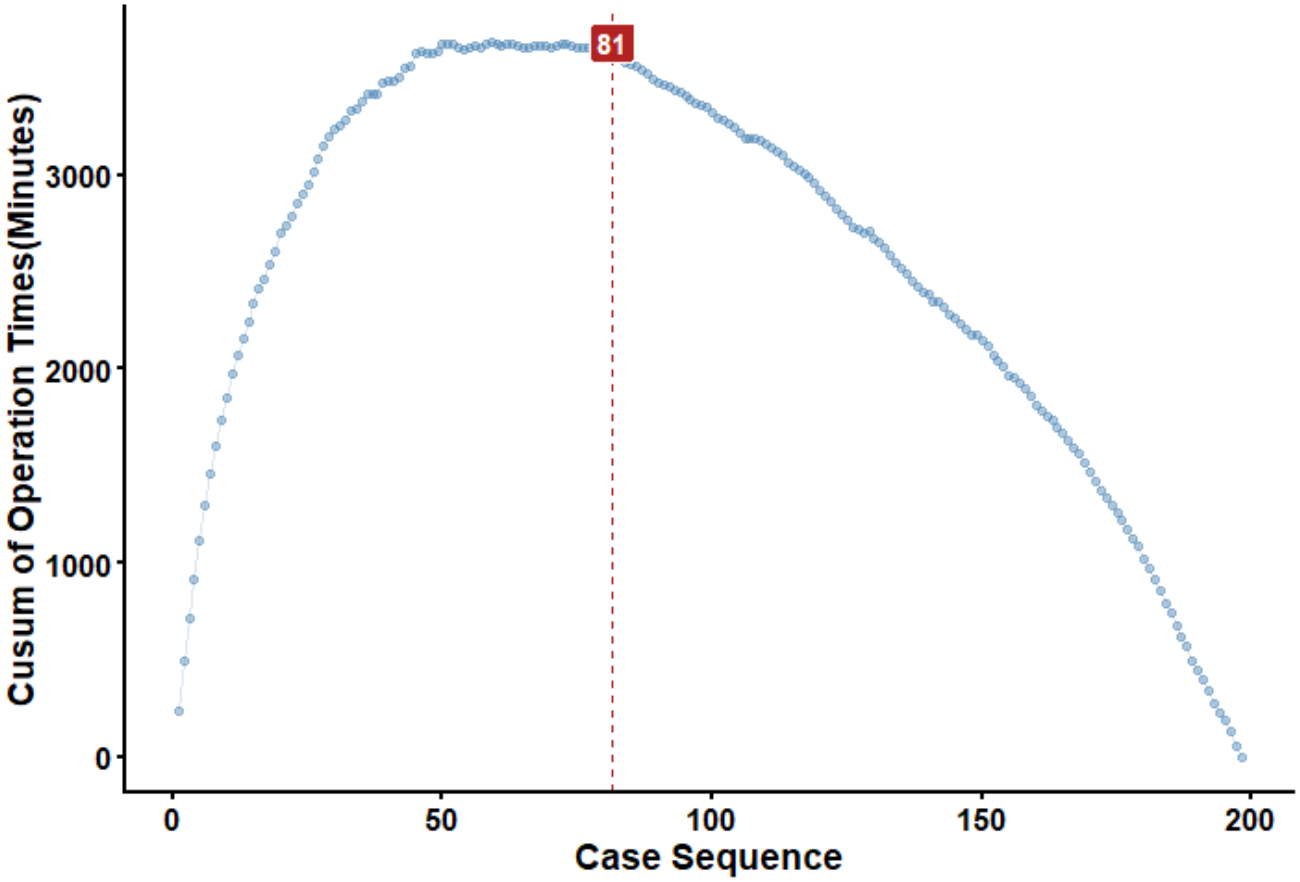


Figure 2 CUSUM learning curve for operation time. The curve reaches a plateau after 81 cases.

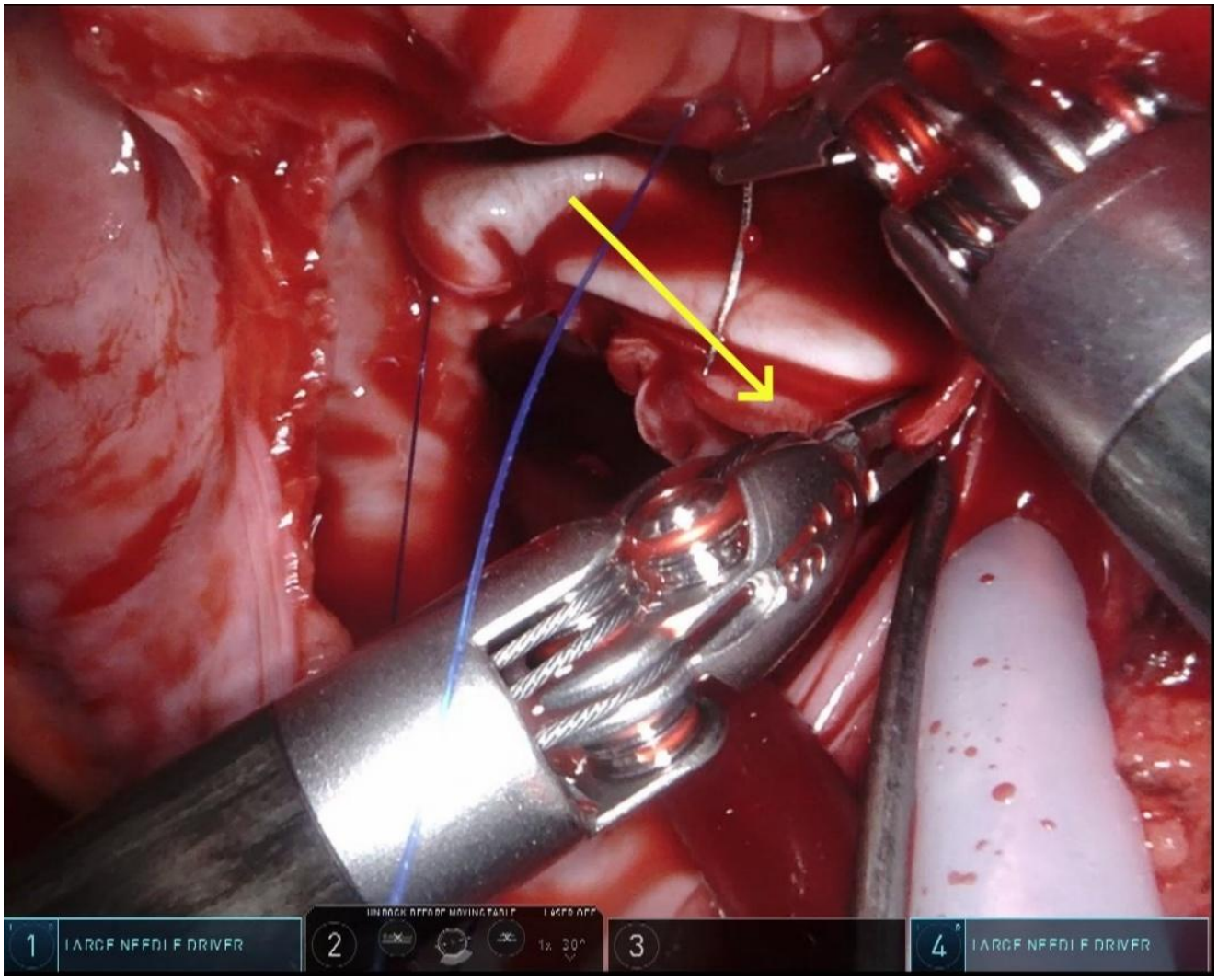


Figure 3a Robotic-assisted exposure of the atrial septal defect (ASD) and partial anomalous drainage of the right inferior pulmonary vein (RIPV).

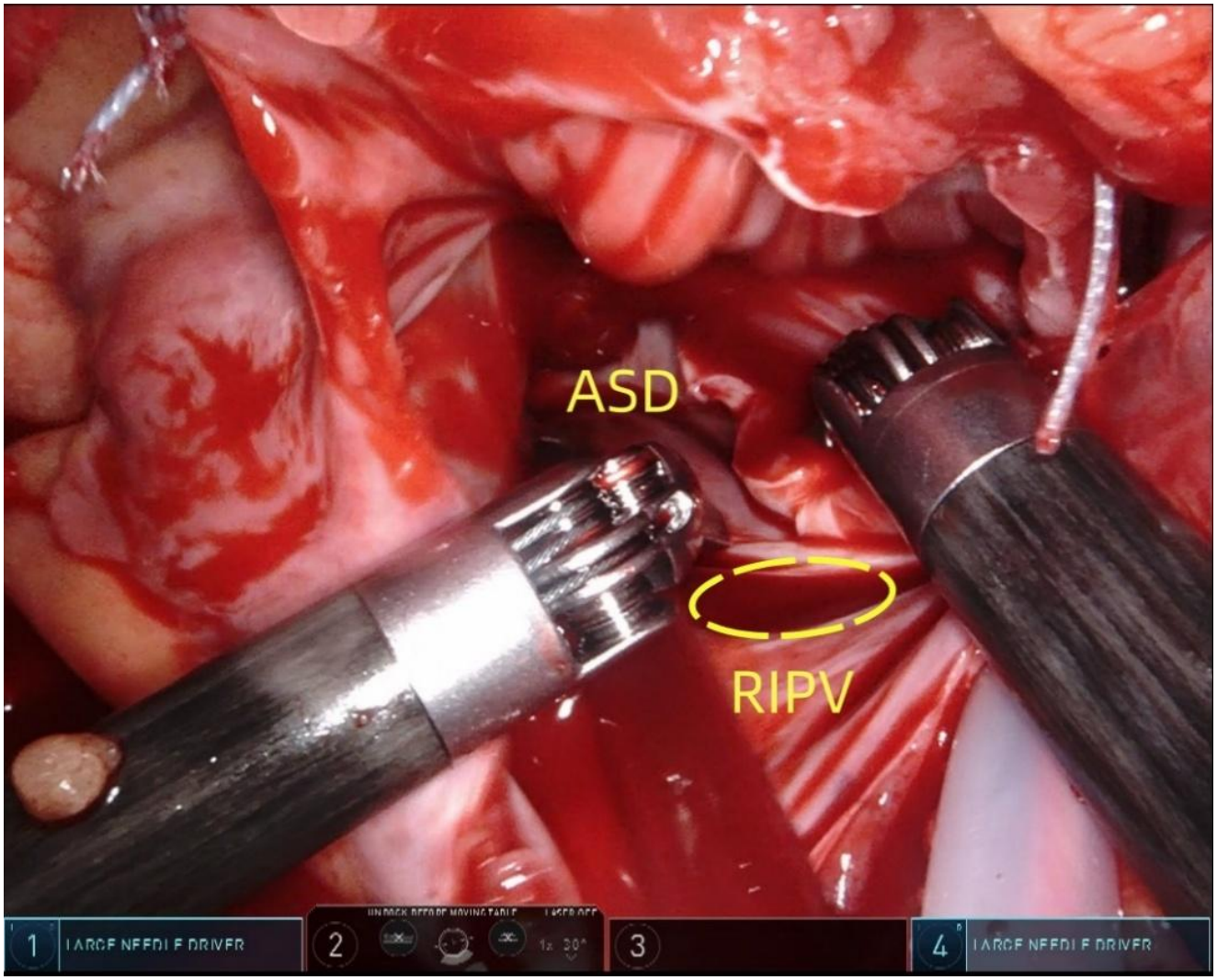


Figure 3b Patch repair of the ASD is initiated at the 10 o'clock position; the smooth surface of the patch faces the right atrial side. The yellow arrow indicates the clockwise direction of suture placement.

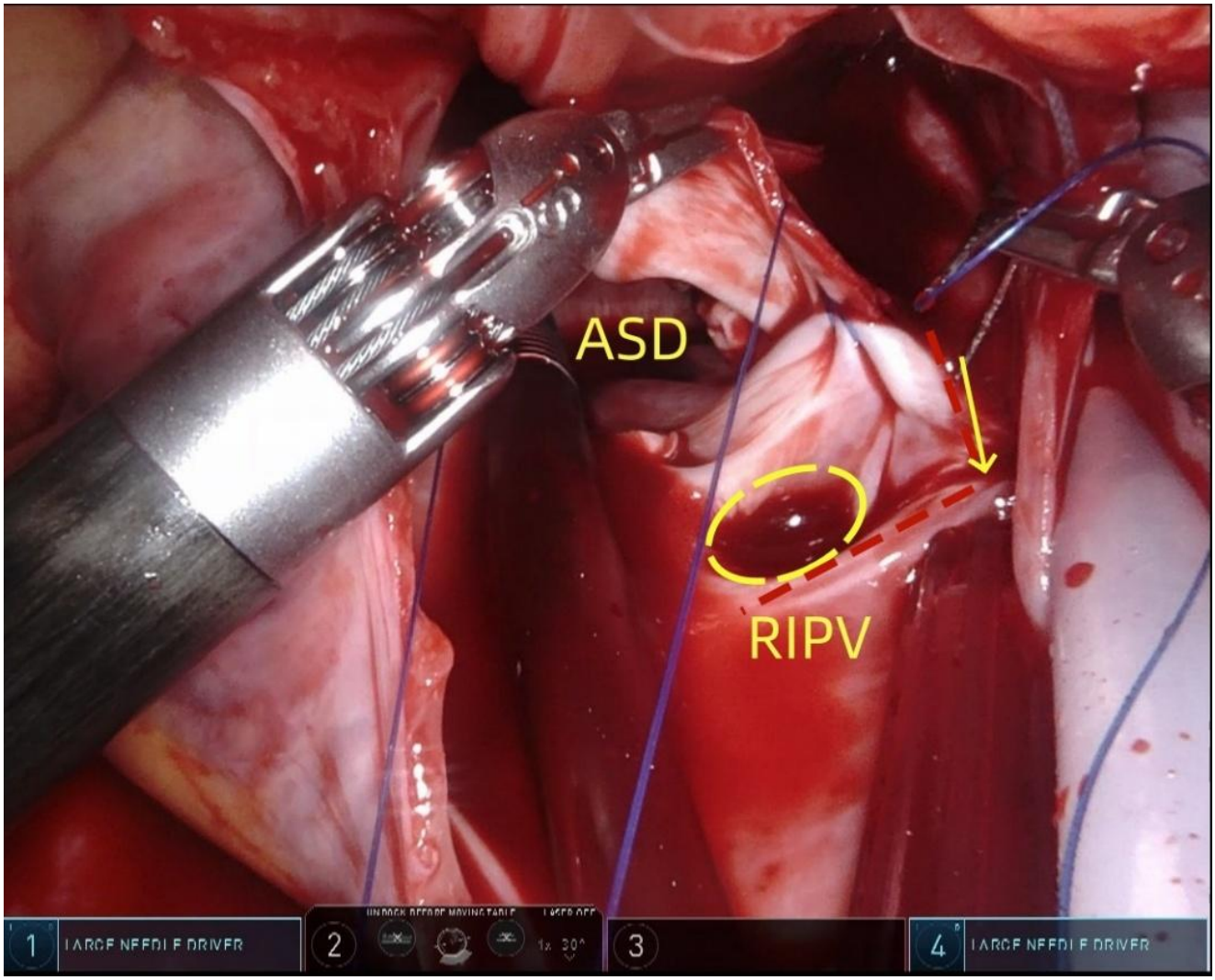


Figure 3c Suturing was continued to the 3 o'clock position, and the patch was then rotated 180°, with its rough surface facing the right atrial side. Yellow arrows indicate the clockwise direction of suturing; the red dashed line marks the suture line. The patch is used to baffle the right inferior pulmonary vein to the left atrial side.

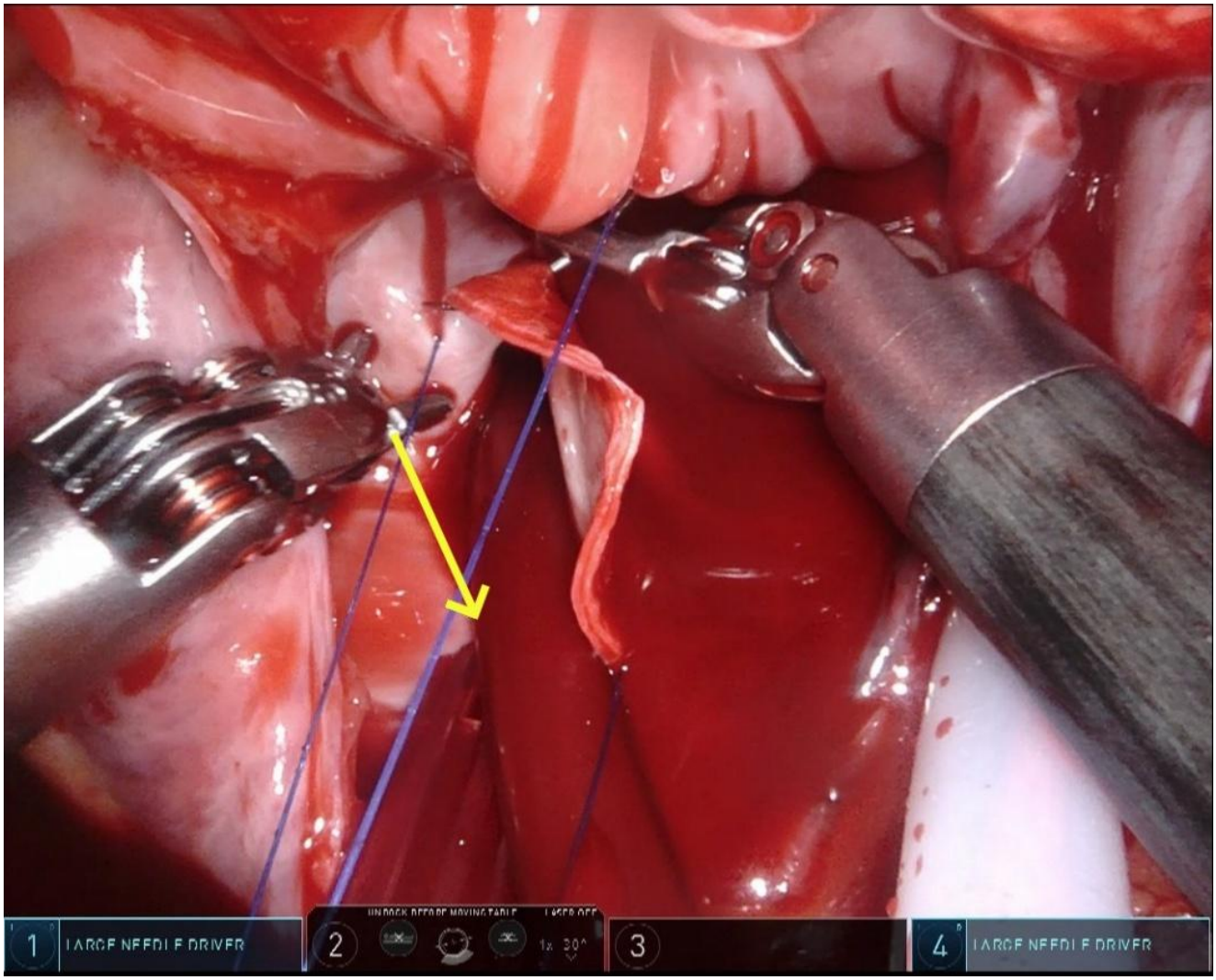


Figure 3d The yellow arrow shows the counterclockwise direction of the second suture.

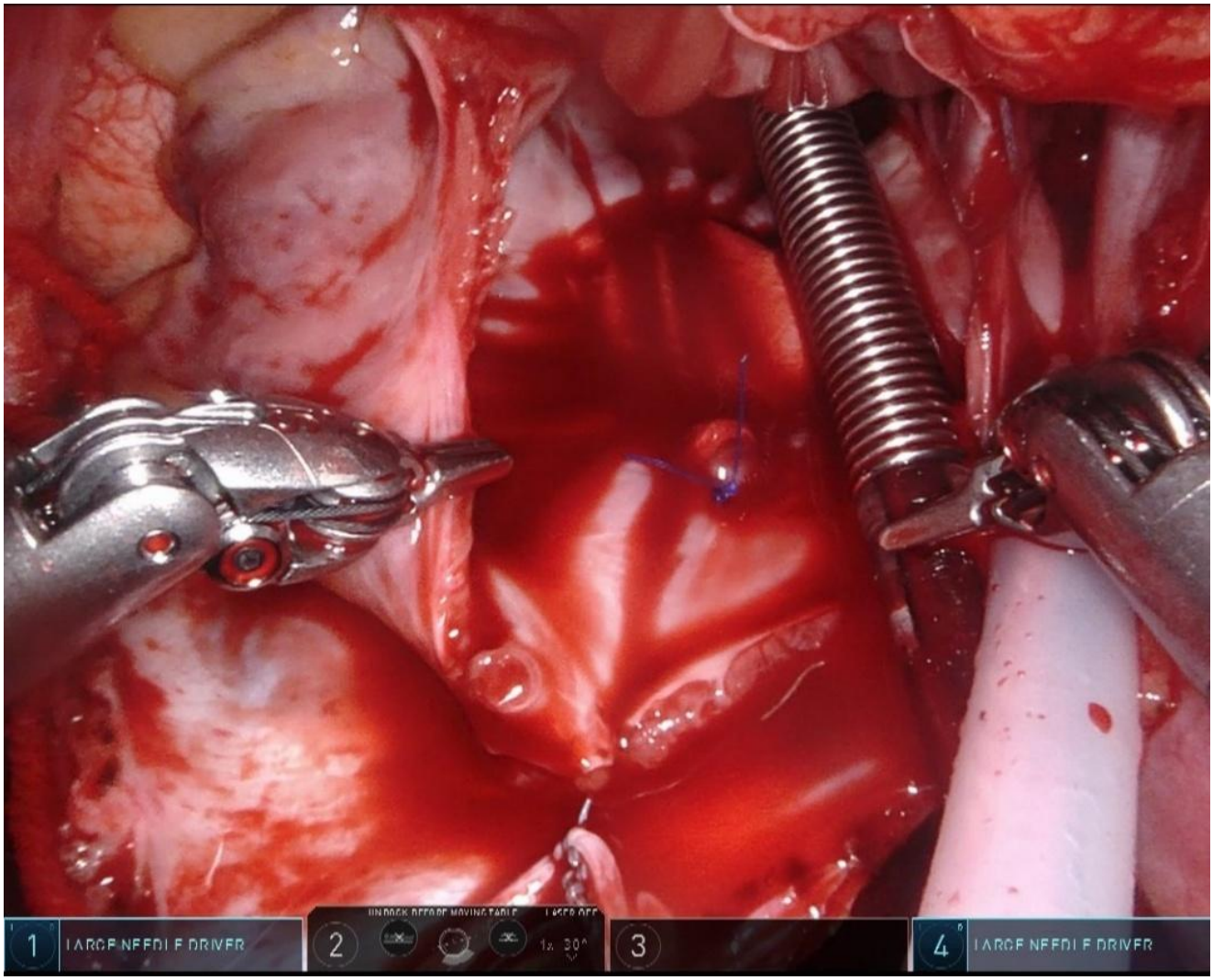


Figure 3e Both needles meet at the 6 o'clock position; the suture is tied after de-airing, and the repair is inspected for any residual shunt.

Tables

Table 1. Baseline characteristics

Variable	Robotic group (n = 117)	Thoracoscopic group (n = 113)	P value
Male/female	32/85	24/89	0.269
Age (years)	36.08 ± 13.61	33.93 ± 11.12	0.191
BSA (m^2)	1.70 ± 0.18	1.68 ± 0.17	0.401
BMI (kg/m^2)	23.15 ± 2.24	22.76 ± 2.12	0.383
LVEF (%)	65.24 ± 3.65	64.41 ± 2.99	0.062
PASP (mmHg)	44.23 ± 6.90	41.96 ± 8.34	0.025
ASD size (mm)	30.10 ± 4.55	28.47 ± 6.29	0.026
PAPVC, n (%)	7 (6.00)	0 (0.00)	0.014
Anomalous vena cava drainage, n (%)	1 (0.85)	0 (0.00)	1
Hypertension, n (%)	4 (3.42)	3 (2.65)	0.994
Diabetes mellitus, n (%)	4 (3.42)	2 (1.77)	0.684
Coronary heart disease, n (%)	0 (0.00)	0 (0.00)	–
Previous cerebral infarction, n (%)	1 (0.85)	2 (1.77)	0.617

BSA, body surface area; BMI, body mass index; LVEF, left ventricular ejection fraction; PASP, pulmonary artery systolic pressure; ASD, atrial septal defect; PAPVC, partial anomalous pulmonary venous connection.

Table 2**.** Surgical data and postoperative outcomes

Variable	Robotic group (n = 117)	Thoracoscopic group (n = 113)	P value
Operation time (min)	141.02 ± 16.25	144.70 ± 16.75	0.092
CPB time (min)	56.27 ± 5.45	59.95 ± 10.90	0.002
Mechanical ventilation time (h)	5.59 ± 2.84	6.17 ± 1.96	0.075
Tricuspid valve repair, n (%)	0.202		
— Kay technique	24 (20.51)	16 (14.16)	
— Annuloplasty	13 (11.11)	8 (7.08)	
Repair of PAPVC, n (%)	7 (6.00)	0 (0.00)	0.014
Correction of anomalous vena cava drainage, n (%)	1	0	1
Postoperative ICU stay (h)	10.81 ± 5.08	11.07 ± 3.90	0.661
Postoperative hospital stay (days)	5.73 ± 2.73	6.13 ± 1.19	0.148
Chest drainage in 24 h (mL)	101.93 ± 57.45	90.66 ± 50.88	0.117
Intraoperative RBC transfusion, n (%)	0 (0.00)	0 (0.00)	–

CPB, cardiopulmonary bypass; PAPVC, partial anomalous pulmonary venous connection; ICU, intensive care unit; RBC, red blood cell.

Table 3. Postoperative complications

Variable	Robotic group (n = 117)	Thoracoscopic group (n = 113)	P value
30-day mortality, n (%)	0 (0.00)	0 (0.00)	–
Postoperative atrial fibrillation, n (%)	5 (4.27)	4 (3.54)	1
Reoperation for bleeding, n (%)	1 (0.85)	0 (0.00)	1
Complication of femoral cannulation, n (%)	0 (0.00)	1 (0.88)	1
Pulmonary hypertensive crisis, n (%)	1 (0.85)	0 (0.00)	1
Delayed mechanical ventilation (>24 h), n (%)	1 (0.85)	0 (0.00)	1
Re-expansion pulmonary oedema, n (%)	1 (0.85)	0 (0.00)	1
Postoperative delirium, n (%)	2 (1.71)	1 (0.88)	1
Postoperative dialysis (AKI), n (%)	1 (0.85)	0 (0.00)	1
Residual defect, n (%)	0 (0.00)	0 (0.00)	–
Wound infection, n (%)	0 (0.00)	1 (0.88)	1

AKI, acute kidney injury.

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