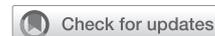# Outcomes of Barlow mitral valve repaired by robot-assisted keyhole surgery

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ABSTRACT

Objective: To present our strategy and the clinical outcomes of robot-assisted Barlow mitral valve keyhole surgery.

Methods: From May 2015 to March 2022, a total of 1281 patients underwent mitral valve repair at our institution, including 763 with robotics surgeries. Of these, 124 patients with Barlow mitral valve (49 ± 12 years, male/female ratio = 81:43) were treated using robotic assistance and included in this study.

Results: All operations were completed using 3 to 5 keyholes. Neochordae implantation using the loop technique was the first option, and resection was performed only in cases with an intrinsic risk of developing systolic anterior motion. Neochordae implantation was performed in 118 cases (95.1%) using 6.6 ± 3.0 neochordae. Posterior leaflet resection was performed in 27 (21.7%) patients. Operation time was 177 ± 42 minutes, cardiopulmonary bypass time was 127 ± 25 minutes, and aorta crossclamp time was 76 ± 16 minutes. Blood transfusion was required in 5 cases (4%). None of the patients required a conversion to valve replacement. The postoperative complications included bleeding (n = 4), stroke (n = 1), and infection (n = 2). Mitral valve regurgitation 1 week after repair was none or trivial in 122 cases (98.3%), mild in 2 cases (1.7%), and more than moderate in 0 cases. Freedom from reoperation was 99.2% during the follow-up period of 36 ± 21 months. One patient required reoperation due to infective endocarditis.

Conclusions: Robot-assisted keyhole surgery using the loop-first concept was adequate to help achieve satisfactory and safe perioperative outcomes for Barlow mitral valve. (JTCVS Techniques 2023;22:16-22)
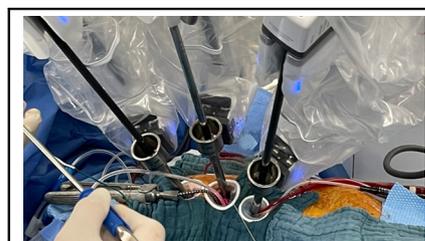
Port placement in robot-assisted keyhole mitral valve repair.

CENTRAL MESSAGE

Robot-assisted keyhole surgery using the loop-first concept is adequate to help achieve satisfactory and safe perioperative outcomes for Barlow mitral valve.

PERSPECTIVE

Surgical methods, strategies, and outcomes of robot-assisted surgery from 3 keyholes are described. Our data represent the benefits of using a robot in correcting Barlow mitral valve. Comfortable manipulation of the subvalvular apparatus allowed corrections in multisegment prolapse with multiple neochoradaes combined with loop technique.

▶ Video clip is available online.

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Mitral valve repair (MVr) for Barlow disease is considered to be complicated due to the mixed pathophysiology of the condition.[1,2] Since the regurgitations are consistent with multiple prolapsed lesions, including both anterior and posterior leaflets, every prolapsed or billowed segment should be corrected

to achieve a clear mitral surface. In addition, owing to its redundant leaflet tissues, especially in the posterior leaflet, the risk of iatrogenic systolic anterior movement (SAM) is a serious consideration during surgical management.[3] However, owing to its abundant leaflet tissues, concerns of tissue shortage to achieve sufficient leaflet coaptation are minor. With the proper strategy, it has high potential of being adequately repaired. In recent years, neochordae implantations have been developed to correcting leaflet prolapses.[4-8] In addition, using the loop techniques, multiple neochordae can be implanted to multiple segments of the prolapsed leaflets.[9]

Similarly, robot-assisted chest keyhole cardiac surgeries have been performed for minimally invasive MVr.[3,10,11] Robotic surgery provided cosmetic benefits in addition to clear visuals of the affected mitral valve and comfortable manipulation of the subvalvular apparatus (Video 1). Therefore, precise analysis and appropriate repair strategies can correct complicated lesions.

Furthermore, retaining the safety of the procedure should not be overlooked during keyhole cardiac surgeries. Herein, we report the outcomes of Barlow valve treatment using robotic MVr and evaluate its quality and safety.

METHODS

From May 2015 to March 2022, a total of 1281 patients underwent MVr at our institution. Of these, 763 were performed using robot-assisted keyhole surgery, and 203 were performed by conventional minimally invasive surgery via right thoracotomy. The number of robotic cases increased
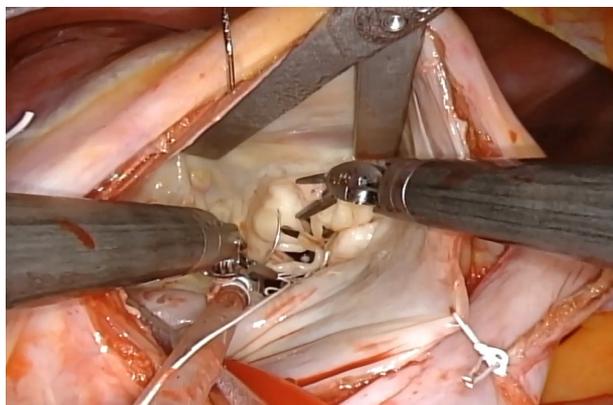
VIDEO 1. Surgical vision of loop technique from the robotic camera. The comfortable visualization and manipulativeness accelerates the multiple neochordae establishments for correcting the leaflet prolapses in Barlow mitral valve. Video available at: https://www.jtcvs.org/article/S2666-2507(23)00385-1/fulltext.

dramatically from the year 2018, due to the national health insurance application for robotic cardiac surgery in Japan. Of these, 124 robotically repaired Barlow mitral valve cases were included in the study (age, 49 ± 12 years; male/female ratio = 81:43). Data were retrospectively collected and evaluated.

Early- to mid-term outcomes were also evaluated. This study was approved by the Ethics Committee of the NewHeart Watanabe Institute, Japan (approval no. 2022-015, September 21, 2022). Written informed consent was given by all participants before the study for publication of their study data.

Surgical Methods

The patient was placed in the supine position, and general anesthesia was delivered through a double-lumen endotracheal tube that allowed for hemipulmonary collapse. A triple-lumen central venous catheter and a Swan-Ganz catheter (Edwards Lifesciences) were inserted in the left jugular vein. A 16-Fr drainage tube was inserted into the right jugular vein with low-dose heparin (3000-5000 units), and transesophageal echocardiography was performed.

Subsequently, the patient was moved to the 30° decubitus position. Cardiopulmonary bypass was established following injection of full-dose heparin. A 22- to 24-Fr drainage canulae was inserted into the right femoral vein. Bicaval and jugular vein drainage were performed. In cases of persistent left superior vena cava, an additional drainage canulae was inserted from the left jugular vein. The first choice for the arterial line was the right femoral artery because of the ease and safety of cannulation. In cases of calcification and plaques in the descending and abdominal aorta, or insufficient diameter of the iliac arteries, the axillary artery was selected as a substitute.

Right-sided thoracoscopic robot-assisted procedure was performed through 3 ports using a surgical robot system (da Vinci Surgical System; Intuitive Surgical). Ten-millimeter ports were inserted on the right anterior axillary line from the third and fifth intercostal space. A camera port combined with a service port 20 mm in diameter was placed in the fourth intercostal space on the right anterior axillary line (Figure 1). In case of patients with obesity, the camera port and the service port were separated for preventing their interference. The retractor port was added only when required. The da Vinci Surgical System was docked onto the patient. After pericardiotomy and marking of the right-side left atriotomy line, double purse-string elastic sutures were placed on the aorta around the planned cardioplegia cannula insertion site. An antegrade cardioplegic needle was passed directly through the chest wall and inserted through the middle of the purse-string suture into the ascending aorta. A flexible aortic crossclamp was endoscopically inserted through the service port. Cardiac arrest was induced using cold cardioplegia. After left atriotomy, the atrial roof was lifted. The lesion was identified using the saline test, and MVr was performed accordingly. The ideal mitral valve leaflet surface was also confirmed using a saline test. Cryoablation of left atrial box lesion and mitral annulus with a designated probe (CryoICE; AtriCure) and endocardial left atrial appendage closure with a 4-0 Gore-Tex suture (CV-4; W.L. Gore & Associates) was performed in a patient with coexisting atrial fibrillation. The atriotomy was closed with 3-0 PROLENE (Ethicon) continuous suture and a left ventricular vent tube was inserted from the incision line. The patient was then placed in the Trendelenburg position and a sufficient dose of hot shot was administered. Thereafter, the aorta was declamped. In patients with coexisting tricuspid insufficiency, tricuspid annuloplasty was performed using the right arteriotomy, with the superior vena cava clamped. During closure of the atriotomy, the cardia was weaned from the cardiopulmonary bypass. Following vent tube extubation, the resolution of mitral regurgitation was confirmed using transesophageal echocardiography. The cardioplegic needle was evacuated from the aorta according to the method described by Watanabe and colleagues.[12] Finally, the robot was undocked, cardiopulmonary bypass was disconnected from the patient, and the incision sites were closed.
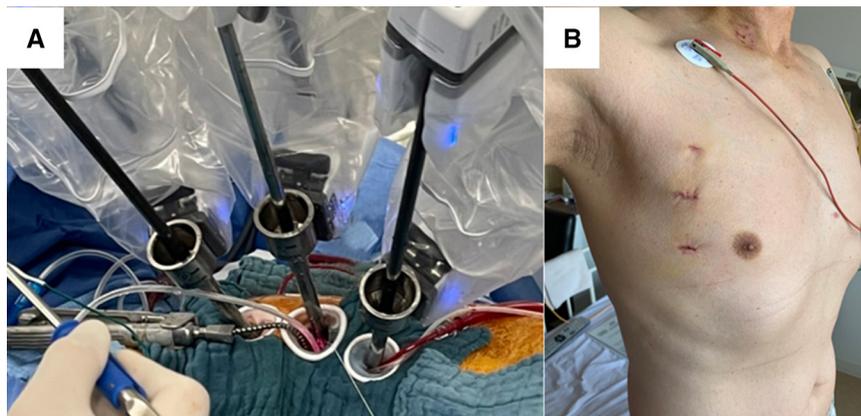
FIGURE 1. A, Positioning of the ports in robot-assisted mitral valve repair. Three keyholes were made in anterior axillary line in the right chest. B, Postoperative scars from the robot-assisted keyhole surgery.

Decision-Making Algorithm for MVr

The MVr was divided into 3 steps (Table 1). Step 1: correction of the prolapse and billowing, which included the selection of neochordae implantation and/or resection of the posterior leaflet. When correcting the prolapse of the anterior leaflet, neochordae implantation was always performed using the loop technique. In contrast, with respect to prolapse of the posterior leaflet, a decision was made to either respect or resect the leaflet. The primary choice was neochordal implantation. Resection was performed only in patients with an excessively long posterior leaflet (>15 mm) and additional risk of iatrogenic SAM. Additional risks included small ventricle, narrow aortomitral angle, thick septum, and hyperdynamic left ventricle.[3]

Step 2: Annuloplasty was conducted depending on the risk of iatrogenic SAM. In the patient with a risk of developing SAM, partial bands were selected, and for the others, full rings were selected.[13] The size of the ring or band was carefully selected to avoid the use of undersized bands/rings to help avoid SAM.[3]

Step 3: Final touch. After administering a saline test, addition or removal of the neochordae, additional suturing of the leaflets, or edge-to-edge repair were performed for the complete correction of regurgitation.

RESULTS

The patients' operative profiles are shown in Table 2. Operation time was 177 ± 42 minutes, cardiopulmonary bypass time was 127 ± 25 minutes, and aorta crossclamp time was 76 ± 16 minutes. Concomitant procedures for atrial fibrillation correction were performed in 16 patients (13%), tricuspid annuloplasty in 29 patients (23%), and the Nuss procedure in 1 patient (0.8%). The axillary artery was used as an arterial line in four patients (3.2%).

Neochordal implantation was performed in 118 patients (95.1%). The average number of implanted neochordae was 6.6 ± 3.0. Leaflet resection was performed in 27 (21%) patients. Full and partial rings were implanted in 57 (46%) and 66 patients (53%), respectively. Edge-to-edge repair was performed in 31 (25%) patients. None of the patients required a second aortic crossclamping during the conversion to valve replacement. No patient developed SAM or mitral stenosis after weaning from cardiopulmonary bypass.

Postoperative data are shown in Table 3. The duration of the procedure until tracheal tube extubation was 5.6 ± 5.3 hours, intensive care unit stay was 1.9 ± 0.7 days, and in-hospital stay was 9.7 ± 5.8 days.

Blood transfusion was required in 5 cases, which accounted for 4% of the total number of patients included. The postoperative complications were bleeding (n = 4, 3.2%), stroke (n = 1, 0.8%), and infection (n = 2, 1.6%). All cases of bleeding originated from the intercostal vessels at the incision site and were stopped using cauterization. The stroke occurred in the peripheral motor field of the right upper hemisphere and caused monoplesia in the left fourth and fifth fingers. One infection occurred at the

TABLE 1. Algorithm for treating Barlow mitral valve robot-assisted keyhole surgery

	Basic strategy	With the risk of SAM
Step 1 　Correction of the prolapse	Neochordae implantation (loop technique)	Resection of excessively tall posterior leaflet
Step 2 　Annuloplasty	Full ring *avoid the undersized ring	Partial ring or band *avoid the undersized ring
Step 3 　Final touch	Addition or removement of the chords Cleft closure Edge-to-edge stitch	

SAM, Systolic anterior motion. *Crucial tip to prevent SAM.

TABLE 2. Operative data

Details of mitral valve repair	
Neochordae implantation, n (%)	118 (95.1%)
Implanted chords, n	6.6 ± 3.0
Resection of posterior leaflet, n (%)	27 (21.7%)
Plication of posterior leaflet, n (%)	4 (3.2%)
Edge-to-edge repair, n (%)	31 (25%)
Annuloplasty, n (%)	123 (99.2%)
Full ring, n (%)	57 (46%)
Average ring size, mm	33.2 ± 2.0
Partial band, n (%)	66 (53%)
Average ring size, mm	32.9 ± 1.9
Concomitant procedures	
Cryoablation and left atrial appendage closure, n (%)	16 (13%)
Tricuspid valve repair, n (%)	29 (23%)
Nuss procedure, n (%)	1 (0.8%)
Profiles	
Operation time, min	177 ± 42
Cardiopulmonary bypass time, min	127 ± 25
Aortic crossclamp time, min	76 ± 16
Repair failure and second crossclamp, n (%)	0 (0)
Conversion to mitral valve replacement, n (%)	0 (0)
Arterial line from axillary artery, n (%)	4 (3.2%)

Data given as n (%) or mean ± standard deviation.

surgical site and presented as empyema that was cured by thoracoscopic debridement and drainage. The other infection occurred on the thoracoplasty bar during the Nuss procedure 6 weeks after surgery and progressed to infective endocarditis. This was resolved with bar evacuation and MVr. No deaths, pacemaker implantations, or renal failures occurred.

Postoperative mitral regurgitation was evaluated by transthoracic echocardiography. The results are shown in Figure 2. Echocardiography was conducted for every patient 1 week after surgery, and the mitral regurgitation grade was

TABLE 3. Postoperative outcomes

Duration under ventilation, hours	5.6 ± 5.3
ICU stay, d	1.9 ± 0.7
In-hospital stay, d	9.7 ± 5.8
Complications	
Iatrogenic SAM	0 (0)
Transfusion required, n (%)	5 (4.0%)
Conversion to median sternotomy, n (%)	0 (0)
Reoperation for bleed, n (%)	4 (3.2%)
Mortality, n (%)	0 (0)
Stroke, n (%)	1 (0.8%)
Pacemaker implantation, n (%)	0 (0)
Renal failure, n (%)	0 (0)
Infection, n (%)	2 (1.6%)

Data given as n (%) or mean ± standard deviation. *ICU*, Intensive care unit; *SAM*, systolic anterior motion.

none or trivial in 121 cases (98.3%) and mild in three cases (1.7%). Six months after surgery, echocardiography was performed in 116 patients. Regurgitation was none or trivial in 102 cases (88.0%) and mild in 13 cases (11.2%); and 1 patient (0.8%) underwent reoperation due to infective endocarditis, as described in the last paragraph. The freedom from reoperation or additional intervention rate was 99.2% at a median follow-up of 36 ± 21 months (Figure 3).

DISCUSSION

Herein, we report the outcomes of treating Barlow mitral valve using robotic keyhole surgery. All the valves were treated by "repair" in initial surgery, with no conversion to replacement or requirement of second aortic crossclamp. Our decision-making algorithm, based on the concept of loop neochordae implantation as a first option, was suitable for correcting Barlow mitral valve using robot-assisted keyhole surgery.

We believe that the key factor for a successful repair is the number of chords. This was possible owing to the loop technique and advantage associated with robotic assistance. By using the loop technique, more than 4 chords could be established from one papillary muscle.[9] Since the prolapsed lesions are multisegmented in Barlow mitral valve, multiple loops on a pledget could correct the prolapse of the respective segments, that is, A1, A2, A3, P1, P2, P3, and commissures. The robotic 3-dimensional camera provided clear visuals and assisted with precise manipulation, measuring the distance from the papillary muscle to leaflet coaptation zone or the distance to annulus, and neochordae establishment was accomplished with ease.[2,10]

Regarding resection, the key role of this technique was to avoid postoperative SAM since excessively long posterior leaflets are highly associated with the risk of developing SAM.[3] We did not correct whole prolapses by resection. Since Barlow valve consists of redundant tissue in multiple segments, multiple resections are sometimes required to control regurgitation. Multiple resections require specific inspection to identify the resected area and are associated with the risk of an irreversible shortening of leaflet tissue. Therefore, to avoid excessive resection, we resected no more than one scallop using preferred triangular resection. When prolapse persisted after resection and suturing, neochordae were added. Using this algorithm, we were able to complete every operation without the need for valve replacement.

Neochordae implantation is also considered to have other advantages in addition to the correction of prolapses. Since neochordae implantation is a reversible technique, they could be removed if the chord length is found to be inappropriate during the saline test. This enabled precise adjustment of the depth of the multiprolapsed leaflets under the clear vision of the robotic camera. Neochordae implantation also helped avoid the selection of undersized rings.[5] Owing
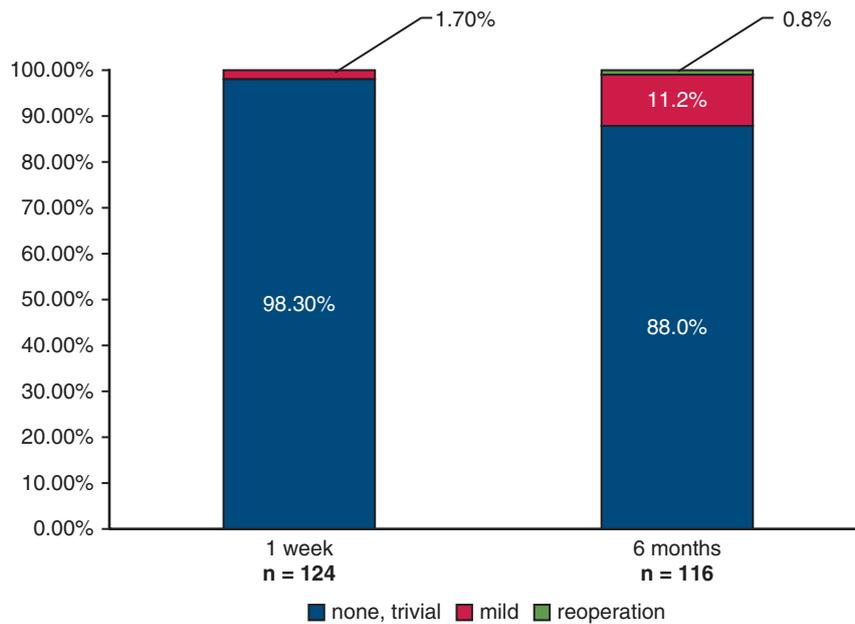
FIGURE 2. Postoperative mitral regurgitation.

to the preservation of leaflet tissues, sufficient coaptation was achieved without excessively reducing the annular size. Prevention of ring undersizing is related to not only avoiding the risk of iatrogenic SAM but also preventing postoperative ring detachment.

The selection of the annuloplasty ring type may be controversial. In this study, the full ring and the partial band were selected for patients at risk of developing SAM. This decision was made according to the report by Loulmet and colleagues.[13] The result was satisfactory,
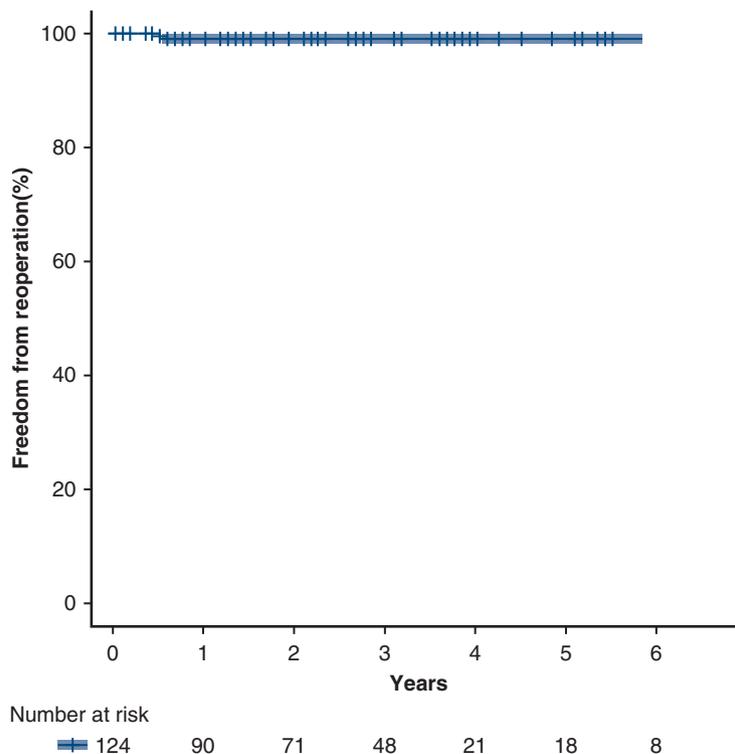

FIGURE 3. Kaplan–Meier curve for freedom from reoperation (95% confidence interval).
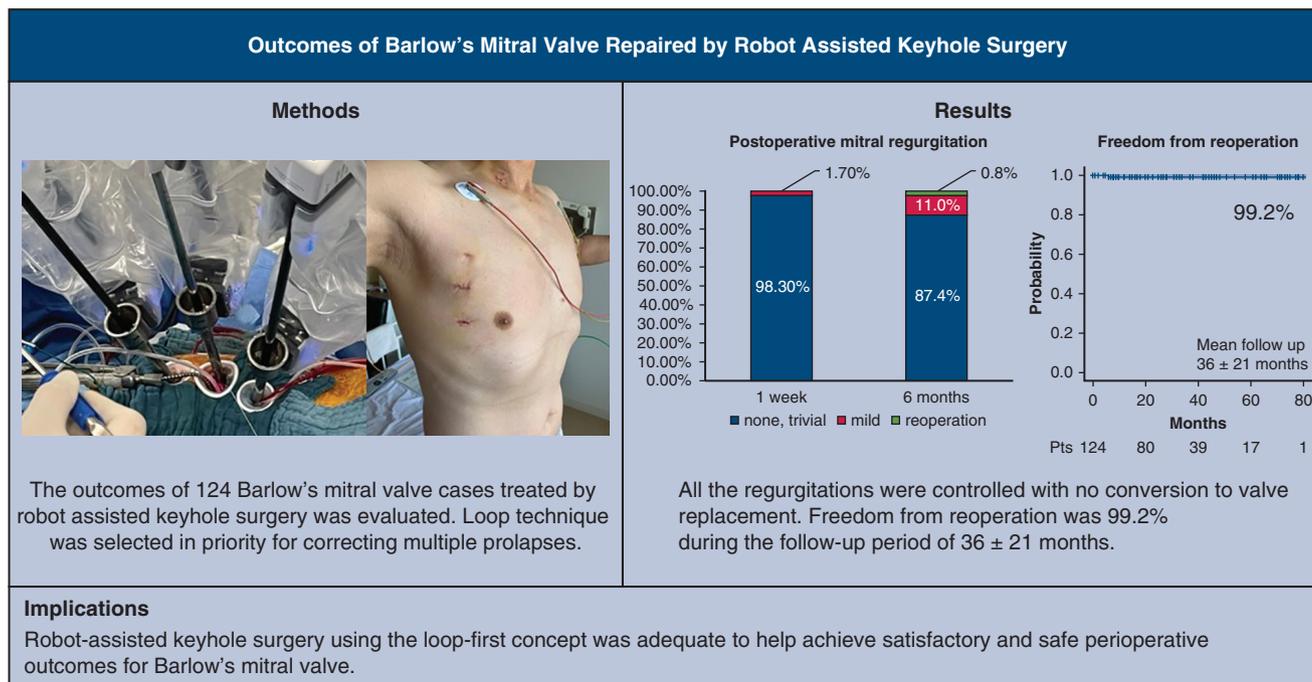
FIGURE 4. Images and outcomes of Barlow mitral valve repaired by keyhole surgery.

with sufficient control of regurgitation and prevention of postoperative SAM. We applied this ring selection not only in Barlow mitral valves but all other MVr procedures. However, since Barlow mitral valve has flourishing coaptation zones owing to the abundant leaflet tissue, we cannot deny the possibility that most of the regurgitation could have been corrected only with partial bands or rings.

Edge-to-edge repair was performed in 25% of patients. It was useful toward correcting regurgitation from the prolapse in the commissures. In addition, it played an important role in correcting the small residual regurgitation between anterior and posterior leaflet after neochordae implantations. The reason for relatively high percentage of edge-to-edge repair was considered to be due to the loop technique's preset chordal height, which may be the disadvantage of our technique. However, by limiting the number of stitches to less than two single interrupted sutures, no mitral stenosis was developed after the repair.

There was no conversion to median sternotomy. Median sternotomy conversion during minimally invasive cardiac surgery is necessary in cases of unplanned bleeding, cardiac ischemia, or low-output syndrome. Unplanned bleeding occurs in left atrial appendage or aorta. When suturing the appendage from the intracardia, a CV-4 suture was used to avoid bleeding from the needle holes. In cases with enlarged appendages, the appendages were left open for later thoracoscopic stapler appendectomy.[14] In order to avoid bleeding from the cardioplegic needle hole in the aorta, a double purse string suture method, as described

by Watanabe and Ishikawa, was used.[12] Specific to robotic operations, liver damage by the port should be avoided with particular awareness. Cardiac ischemia during MVr occurs due to damage of the circumflex artery during ring annuloplasty.[6] To avoid this, it is crucial to check the route of the circumflex artery preoperatively using 3-dimensional computed tomography or coronary artery angiography. Furthermore, for smooth weaning from cardiopulmonary bypass, coronary artery deairing using retrograde blood flow from the coronary sinus, as reported by Miyata and colleagues,[15] is effective.

Stroke prevention should be prioritized to maintain the safety of keyhole surgery. In this study, the incidence of stroke was 0.8%. Therefore, precise care should always be taken to reduce the risk of stroke. For example, in cases of moderate-to-severe atherosclerosis and plaques in the aorta, concerns of cholesterol embolism due to retrograde perfusion should be considered. In these cases, an additional arterial line to axillary arteries must be established. In addition, Trendelenburg positioning during aortic declamping and cardiopulmonary bypass weaning is also important to help avoid air embolism and maintain cerebral circulation. Although time-consuming, it is important to undock the robotic ports once and change the body position.

Study Limitations

This study demonstrates an optimal method for achieving satisfactory and safe perioperative outcomes. However,

because the mean follow-up period was 36 months, the durability of the repaired valves remains unknown. A long-term follow-up (approximately 10 years) is required to confirm the efficacy of the procedure.

Almost all of the patients received postoperative echo in our institute 1 week and 6 months after the surgery. However, the echo afterwards was followed by local clinics, and not all the echo data could be collected. This would also be the limitation of this study.

CONCLUSIONS

Robot-assisted keyhole surgery using the loop-first concept is adequate for achieving qualified and safe perioperative outcomes in Barlow MVr. See Figure 4 for a graphical abstract of the study.

Webcast

You can watch a Webcast of this AATS meeting presentation by going to: https://www.aats.org/resources/the-outcomes-of-barlow-s-mitral-valve-repaired-by-robot-assisted-keyhole-surgery.

Conflict of Interest Statement

The authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

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