

Endoscopic robotic mitral valve surgery

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See related editorial on page 753.

Objective: To determine the safety and efficacy of endoscopic mitral valve surgery using robotic instruments through the lateral right chest.

Methods: We conducted a retrospective review of 127 patients taken to the operating room for endoscopic robotic mitral surgery from December 2002 through November 2005. Mean age was 54 ± 13 years and 58% were male. Mitral regurgitation was 4+ in 121 patients, 3+ in 4 patients, and 2+ in 2 patients. Nineteen (15%) patients had a left ventricular ejection fraction of 0.50 or less. Surgical approach was through 4 right chest ports with femoral perfusion and endoaortic balloon occlusion. Mean follow-up was 13.7 ± 8.9 months and was 100% complete. Echocardiographic follow-up was available on 98 patients with a mean of 8.4 ± 8.1 months.

Results: The mitral procedure was completed endoscopically in 121 (95%) patients. Mitral valve repair was performed in 114 patients and mitral valve replacement in 7 patients. Two patients required reoperation on the mitral valve. There was 1 (0.8%) hospital death and 1 late death. Echocardiographic follow-up in 98 survivors of endoscopic mitral repair revealed 0-1+ regurgitation in 95 (96.9%) and 2+ in 3 (3.1%) patients.

Conclusions: Totally endoscopic mitral surgery can be performed safely with robotic instrumentation. A right lateral configuration of the robotic system allows excellent visualization of the valve with minimal distortion and permits two surgical personnel to participate actively in valve instrumentation. In selected patients with mitral valve disease, this surgical approach might promote higher rates of valve repair.

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The value of a mitral valve operation is directly related to the efficacy of the procedure performed on the valve and inversely related to the invasiveness necessary to achieve it. This value can be maximized if a high rate of successful valve repairs can be achieved with a least invasive approach. Although the principles of mitral valve repair were described more than 20 years ago,¹ the repair rate for isolated mitral valve disease in the United States remains below 50%.^{2,3} Mitral valve repair requires the surgeon to understand mitral valve pathophysiology and to have a surgical strategy to correct it.⁴ Even armed with this knowledge, however, the surgeon must have the ability to expose the valve and successfully instrument it. The advantages of mitral valve repair over replacement involve potentially lifelong benefits to the patient, including preservation of ventricular function and avoidance of anticoagulation.⁵ Any change in surgical ap-

proach to mitral valve surgery primarily has to afford the surgeon the opportunity to expose and instrument the mitral valve structures and achieve a maximum valve repair rate. The advantages of performing the mitral procedure through a less invasive approach include the potential benefits of fewer wound complications, less blood loss, faster recovery, and a more acceptable cosmetic result, but these advantages are of a more transitory nature and must have a lower priority than achieving valve repair. Possibly because of limitations in exposure and instrumentation and prolonged operative times, minimally invasive approaches to mitral valve repair have not been widely applied.^{6,7} In an effort to maximize the value of mitral valve procedures, we reviewed the landmark work of Starr and Edwards⁸ published in 1963 on mitral valve surgery using a lateral right chest approach to the left atrium. Illustrations of their direct approach to the mitral valve through the left atrium demonstrate excellent exposure and minimal distortion of the valve structures while employing limited retraction of the atrial septum. Starr used a large right thoracotomy and conventional instruments to perform mitral procedures through this approach. Over 40 years later with development of peripheral catheter-based cardiopulmonary bypass⁹ and robotic instrumentation technology,¹⁰ we report on our initial effort to duplicate the exposure and instrumentation experienced by Starr while providing the patient the benefits of a totally endoscopic procedure.^{11,12}

Methods

From December 2002 through November 2005, a total of 127 patients were taken to the operating room for endoscopic robotic mitral surgery. These patients represent 57% of our patients undergoing isolated mitral surgery during the 3-year period. Patients with a heavily calcified mitral annulus, right pleural scarring, or severe aortoiliac atherosclerosis were routinely approached by median sternotomy. Patients with previous median sternotomy or need for concomitant tricuspid repair were approached by minithoracotomy. All patients were fully informed of their surgical approach options.

Patient Characteristics

The mean age of the patients was 54 ± 13 years (21-78 years) and 58% were male. New York Heart Association functional class was I in 11 (8.7%) patients, II in 55 (43.3%) patients, III in 45 (35.4%) patients, and IV in 16 (12.6%) patients. A history of hypertension was present in 62 (48.8%) patients and a history of continuous or intermittent atrial fibrillation was present in 17 (13%) patients. Mean body mass index was 27.2 ± 17.2 (17-30.5). Twenty patients (16%) had a body mass index over 30 and 3 patients had an index over 35. Two patients had pectus excavatum. Preoperative mitral regurgitation assessed by echocardiography was 4+ in 121 patients, 3+ in 4 patients, and 2+ in 2 patients (1 with an atrial septal defect and 1 with an accessory mitral leaflet obstructing left ventricular outflow¹³). Mean left atrial size was 44.9 ± 7.6 mm. Mean left ventricular end-diastolic diameter was 52.7 ± 8.8 mm.

TABLE 1. Echocardiographic and operative mitral valve characteristics (n = 127)

Variable	n	%
Carpentier classification		
Type 1	12	9.4
Type 2	108	85.0
Anterior prolapse	15	11.8
Posterior prolapse	67	52.7
Bileaflet prolapse	26	20.4
Type 3	7	5.6
Valve pathology		
Degenerative	107	84.3
Fibroelastic deficiency	72	56.7
Barlow	35	27.6
Isolated annular dilatation	12	9.4
Rheumatic	5	3.9
Congenital	1	0.8
Radiation induced	1	0.8
Hypertrophic cardiomyopathy	1	0.8

Preoperative mean left ventricular ejection fraction was $57.9\% \pm 9.2\%$ (25%-75%). Nineteen (15%) patients had a preoperative left ventricular ejection fraction of 50% or less. All patients underwent functional valve assessment by transesophageal echocardiography and classification according to Carpentier with valve disease confirmed at surgery (Table 1). All procedures were elective except in 2 patients who required urgent surgery for refractory congestive heart surgery.

Surgical Technique

The patient is intubated with a double-lumen endotracheal tube and transesophageal echocardiography is used by the anesthesiologist to position coronary sinus cardioplegia and pulmonary artery vent catheters. After the patient has been positioned in the supine position with the right side of the chest elevated, the femoral vessels are exposed. The right lung is then deflated and the endoscope of the da Vinci Robotic Surgical System (Intuitive Surgical, Sunnyvale, Calif) is inserted through a 12-mm port placed in the fourth or fifth intercostal space at or just medial to the right anterior axillary line. The 30° up endoscope with the “wide angle” da Vinci camera is moved manually to confirm access to the mediastinum. The handle of the atrial septal retractor is then inserted through a 16F introducer set (Cook, Bloomington, Ind) in the same intercostal space as the endoscope just lateral to the right internal thoracic artery. The endoscope is removed and a 37-mm service port incision is made in the same intercostal space 20 to 30 mm lateral to the endoscope port. With the surgeon’s finger in this service port to protect intrathoracic structures, trocars for the robotic instrument arms, 14-gauge angiocatheters for traction sutures and infusion of carbon dioxide, and a 20F DLP cardiac sump (Medtronic, Inc, Minneapolis, Minn) for left atrial suction are inserted. Right chest preparation is depicted in Figure 1.

The patient is then heparinized and the femoral vessels are cannulated for Port Access¹¹ (Cardioventions, Somerville, NJ).



Figure 1. Right chest port preparation. *E*, endoscopic; *L*, left robotic arm; *S*, service port; *R*, right robotic arm; *V*, left atrial suction catheter.

The da Vinci instrument cart is rolled to the patient's left side and the instrument arms and endoscope are placed in their respective ports. A 20-mm. flexible port (Ethicon Endo-Surgery, Cincinnati, Ohio) is temporarily placed in the service port incision. The surgeon moves to the da Vinci console. The first assistant moves to the patient's right side. Manual occlusion of the service port allows carbon dioxide insufflation to create working space in the right side of the thorax. Pericardiotomy is performed robotically and traction sutures on the pericardium and diaphragm are drawn out laterally through the angiocatheters. The endoscope is then changed to the "high mag" da Vinci camera. Cardiopulmonary bypass is initiated, endoaortic balloon occlusion is achieved, and cardioplegic solution is administered. A hardshell port (ATS Medical, Minneapolis, Minn) is then positioned in the service port. The left atrium is opened at the junction of the pulmonary veins. A 35-mm wide atrial septal retractor blade is passed through the service port into the left atriotomy and connected to the previously placed handle. The atrial septum is retracted to visualize the mitral valve with the 30° up endoscope. Surgical tasks on the mitral structures are then performed with the two robotic instrument arms assisted by the patient-side assistant using shafted instruments through the service port. Running suture lines are facilitated by use of a suture retrieval hook (ATS Medical), allowing the suture needle to be retained in the robotic needle driver. All knot tying is performed extracorporeally by the assistant using a shafted knot pusher. Mitral repair techniques are the same as those that we use on conventional mitral approaches except for the use of V-100 nitinol clips (Medtronic, Minneapolis, Minn) for flexible annuloplasty band or ring attachment.¹⁴ All mitral valve replacements are performed with pledget-supported sutures placed robotically and then passed through the sewing ring and tied extracorporeally by the assistant. Valve sizers (ATS Medical) designed to be compatible with robotic instruments are used. Concomitant left atrial ablation, when indicated, is

TABLE 2. Conversions from endoscopic robotic approach

Patient No.	Reason for conversion	Procedure
1	Ruptured breast implant	Repair through MS
6	Insufficient venous return	Repair through MS
9	Vision system failure	Replacement through MS
19	Femoral arterial disease	Repair through MS
22	Insufficient working space	Repair through MT
87	Marked aortic tortuosity	Repair through MS

MS, Median sternotomy; *MT*, minithoracotomy.

performed by cryoablation catheter (Cryocath, Montreal, Quebec, Canada) through the service port. Left atrial appendage closure is performed with running polytetrafluoroethylene suture (Gore-Tex suture; W. L Gore & Associates, Inc, Flagstaff, Ariz). Deairing is achieved by placing the flexible left atrial suction catheter across the repaired mitral valve at the time of left atrial closure. With valve replacement, the left atrial suction catheter remains in the left atrium and the mechanical valve is maintained incompetent with a small Foley catheter.

Follow-up

Durability of the repair was measured by echocardiographic valve function and the incidence of valve reoperation. Patient follow-up was performed in December 2005 to obtain clinical and echocardiographic status with data expressed as means \pm standard deviation. The mean follow-up was 13.7 ± 8.9 months (0.5-36 months) and was 100% complete.

Results

Technical Feasibility

Conversion to a median sternotomy incision was necessary in 5 patients and to a small thoracotomy with rib spreading in 1 patient (Table 2). All patients recovered uneventfully. The mitral procedure was completed endoscopically in 121 patients (95%). Mitral valve replacement was necessary in 7 (5.8%) of the 121 patients. The valve pathology was Barlow disease in 3 of these 7 patients, endocarditis in 2 patients (1 infectious and 1 Libman-Sacks endocarditis), radiation-induced valve damage in 1 patient, and hypertrophic obstructive cardiomyopathy in 1 patient. All patients received mechanical valves. Mean aortic occlusion time was 146 ± 20 minutes (126-183 minutes) and mean cardiopulmonary bypass time was 182 ± 27 minutes (154-236 minutes). Intraoperative transesophageal echocardiography revealed appropriate prosthesis function in all patients undergoing valve replacement. Mitral valve repair was completed in 114 patients. The techniques used for mitral valve repair as well as concomitant procedures are presented in Table 3. Mean aortic occlusion time was 102 ± 28 minutes (47-182 minutes) and mean cardiopulmonary bypass time was 131 ± 34 minutes (72-234 minutes). Inotropic support was necessary to wean from cardiopulmonary bypass in 18 (15%) patients treated by endoscopy, and no patient re-

TABLE 3. Valve repair techniques and concomitant procedures (n = 114)

Repair or procedure	n	%
Posterior leaflet resection	77	67.5
Anterior leaflet resection	15	13.2
Polytetrafluoroethylene neochordae	26	22.8
Anterior leaflet plication	2	1.7
Commissurotomy	2	1.7
Leaflet pericardial patch	2	1.7
Annuloplasty ring	6	5.3
Annuloplasty band	107	93.9
Atrial ablation	8	7.0
Left atrial appendage closure	8	7.0
Pericardial patch of atrial septal defect	1	0.8
Suture closure of patent foramen ovale	8	7.0

quired an intra-aortic balloon pump. One patient with preoperative complete heart block required temporary pacing. Mitral regurgitation was grade 0 in 104 (91.3%) patients, grade 1+ in 9 (7.9%) patients, and grade 2+ in 1 (1.8%) patient among those undergoing mitral repair.

Perioperative Course

There was 1 hospital death (0.8 %). A 75-year-old man required mitral valve replacement through a median sternotomy for severe systolic anterior motion 1 day after mitral valve repair. His subsequent course was complicated by stroke and multisystem failure with death on postoperative day 48. Postoperative complications are detailed in [Table 4](#). Transfusion of blood products was required in 37 (31%) patients. Three (2.5%) patients were returned to surgery for bleeding. In 2 patients the exploratory procedure was done through the existing ports for bleeding from intercostal sites, but 1 required a median sternotomy for bleeding from the left atrial suture line. The total number of all patients who required a median sternotomy incision during the 3-year experience was 7 (5.5%). One patient who presented in complete heart block received a permanent pacemaker. Two patients required mechanical ventilation for more than 24 hours, and except for the patient who died, no patient had respiratory failure. Intensive care unit stay was less than 24 hours in 94% of mitral repair patients and 57% of mitral replacement patients. The mean stay from surgery to discharge in mitral repair patients was 4.5 ± 2.7 days (2-48 days), with 62 % of patients discharged in 4 days or less. The mean stay after surgery for mitral valve replacement was 9.1 ± 7.5 days (4-25 days). No patient was discharged to extended care.

Postoperative Outcome

Five patients (0.4%) were readmitted within 30 days of discharge: 3 for atrial fibrillation, 1 for groin wound cellulitis, and 1 for gastrointestinal hemorrhage. One patient had

TABLE 4. Postoperative complications (n = 121)

Type of complication	n	%
New-onset atrial fibrillation	22	18.2
Myocardial infarction	0	0
Low cardiac output	0	0
Pneumonitis	2	1.6
Ventilation > 24 h	2	1.6
Prolonged air leak	1	0.8
Right pleural effusion	2	1.6
Chest incision infection	0	0
Transient renal dysfunction	1	0.8
Stroke	2	1.6
Limb ischemia	0	0
Deep venous thrombosis	0	0
Aortic dissection	0	0
Groin wound cellulitis	1	0.8
Groin lymphocele	2	1.6

a paravalvular leak 6 weeks after mitral valve replacement and underwent successful repair through a minithoracotomy. There was 1 late death of a patient with dilated cardiomyopathy treated with ring annuloplasty who died suddenly 2 months after mitral repair surgery. Follow-up echocardiogram 1 month postoperatively had revealed only mild regurgitation, and at autopsy the valve repair was intact. Of the 121 patients whose operations were completed endoscopically 107 (88.4%) had returned to full activity level by 3 weeks after the operation. The New York Heart Association functional class in 119 surviving endoscopic patients was class I in 109 (91.6%) patients, class II in 8 (6.7%) patients, and class III in 2 (1.7%) patients. Postdischarge echocardiographic results were available in 98 mitral valve repair patients with a mean follow-up of 8.4 ± 8.1 months (1.5-33.4 months). Eighty-seven (88.8%) patients had 0 regurgitation, 8 (8.2%) patients had 1+ regurgitation, and 3 (3.1%) patients had 2+ regurgitation.

Discussion

With a right thoracotomy involving the entire fifth intercostal space, Starr was among the first surgeons to gain excellent exposure of the mitral valve and successfully replace it with the use of conventional instruments. The right lateral thoracotomy was subsequently abandoned in favor of the median sternotomy, which allows direct access to the ascending aorta and all cardiac structures. For mitral valve exposure, however, either substantially more atrial septal retraction or more extensive cardiomyotomy is required than with the right thoracotomy approach.¹⁵ For the past decade, in patients at low risk for retrograde femoral artery perfusion, surgeons have labored to return to the lateral approach using a small right anterolateral thoracotomy with or without rib spreading, shafted surgical instruments, and 2-dimensional endoscopy.^{11,15-18} Widespread adoption of this

approach has been impeded by concerns regarding limitations of 2-dimensional vision, challenging instrumentation, and incomplete deairing.^{15,17} Using this same anterolateral approach, Nifong and associates¹⁰ demonstrated that robotic instrumentation could be used for complex mitral repair with the advantages of 3-dimensional vision and enhanced instrumentation. By marrying the technologies of endoaortic balloon occlusion with robotic instrumentation, we have evolved back to the more lateral thoracic approach to the mitral valve described by Starr without the morbidity of a large thoracotomy. The endoaortic balloon technology is an important ingredient in moving this approach laterally because this catheter has antegrade cardioplegia and venting capability and hence requires no direct instrumentation of the ascending aorta. Approaching the mediastinum from the more lateral chest allows more working space for pericardiotomy and placement of traction sutures before initiating cardiopulmonary bypass. Since the approach is endoscopic, this working space can be enhanced by pressurizing the right pleural space by insufflation of carbon dioxide. This technique also has the advantage of creating high carbon dioxide levels in the left cardiac chambers, potentially reducing the risk of air embolism.¹⁹

The lateral endoscopic robotic mitral approach has afforded this series of patients cardiac surgery with minimal chest wall trauma. More important, it has afforded a high mitral valve repair rate, which we attribute to enhanced visualization of the valve, robotic instrumentation, and active participation of the patient-side assistant.

Although excellent visualization of the mitral valve can often be achieved with 2-dimensional endoscopy, the absence of depth perception can be a significant handicap in complex mitral repair.¹⁵ Even minor adjustments of the endoscope to improve the visual field require the surgeon to interrupt surgical activities with handheld instruments. Alternatively, the surgeon can achieve 3-dimensional vision through the chest incision, but this usually requires rib spreading and positioning of the surgeon's head to the focal length of magnifying loupes. With the da Vinci Robotic System, the dual-camera endoscope provides 3-dimensional vision to the surgeon and 2-dimensional vision to the assistants. The console surgeon can adjust the visual field of the endoscope without releasing the instrument controls. Nifong,¹⁰ Reade,¹⁴ and their colleagues described the robotic endoscope inserted through an anterolateral thoracotomy. With the endoscope inserted more laterally near the anterior axillary line, the amount of atrial septal retraction necessary to visualize the mitral structures is reduced. Less atrial septal retraction is valuable in reducing valve distortion.

Instrumentation of the mitral structures with handheld shafted instruments can be very challenging. A more lateral approach, large thoracic size, obesity, and pectus excavatum all increase the distance from the skin to the mitral struc-

tures and increase this challenge. Also, unlike the large thoracotomy approach described by Starr, in which the surgeon's wrists could be placed inside the thorax, the minimally invasive surgeon's wrists remain extracorporeal, permitting only limited manipulations of the valve structures with shafted instruments. With the surgeon holding two shafted instruments nearly parallel through the small thoracotomy or working port, instrument interactions can be difficult or even conflicting. The da Vinci robotic instruments extend 24 cm from the pivot point in the chest wall to the instrument wrist, providing a stable instrument platform at or below the mitral annulus in almost all clinical situations. Although the robotic instrument wrists are not as mobile as human wrists, they are positioned intracorporeally near the instrument tip and provide adequate degrees of freedom for tissue and suture manipulation.¹⁰ In addition, unlike shafted instruments, which are routinely used through a single intercostal space, the robotic instruments are inserted 2 to 3 intercostal spaces apart and are triangulated with the endoscope, mimicking conventional surgical orientation and minimizing conflicts.

Although the vision and instrument advantages of the da Vinci Robotic System are important in the mitral repair capability of this lateral endoscopic approach, the greatest advantage is the ability of the patient-side assistant to participate actively in the instrumentation of the valve. Two factors create this enhanced assistant role. First, the robotic instruments are delivered into the operative field from the instrument cart, which is positioned at the patient's left side. This orientation allows the assistant to stand on the patient's right side with access to the operative field through the service port. Second, in contrast to the anterolateral approach, when the service port is positioned lateral to the endoscope and between the robotic arms, the assistant's instruments can reach the mitral structures directly with minimal interference from the atrial retractor blade, endoscope, or robotic instruments. By having up to 4 instruments at the operative site (2 handheld, 2 robotic), surgical tasks can be greatly facilitated. Cutting and suturing can be performed by the console surgeon, who has 3-dimensional vision and intracorporeal robotic wrists, while suctioning of blood, retraction, and suture retrieval can be simultaneously performed by the patient-side assistant. All knot tying can be performed by the patient-side assistant under the endoscopic surveillance of the console surgeon. In our experience, extracorporeal tying can be performed faster and more accurately than robotic tying. This teamwork is particularly helpful in the construction of new polytetrafluoroethylene chordae where the proper length of the new chord is maintained with the robotic instruments while the assistant performs the knot tying. This synergism between the console surgeon and the patient-side assistant was a major factor in the high valve repair rate achieved in this series of patients.

The duration of follow-up in this report is short, and long-term durability of these mitral procedures remains to be validated, although the outcome may be more a reflection of the repair techniques used than of the instrumentation and approach employed. This technique uses retrograde femoral artery perfusion and should not be applied in patients with advanced atherosclerosis or marked tortuosity of the aorta. Cardiopulmonary bypass duration was relatively long with this approach, although morbidity was comparable with or better than the national data.² Aortic occlusion time was also long with this technique, especially if valve replacement was necessary, but was well tolerated as evidenced by excellent postoperative function. It should be noted that retrograde cardioplegia was used in nearly every patient. A possible major limitation of this technique is the increased operative costs of robotic instrumentation and catheter disposables. Much of this increased cost, however, might be offset by the lower costs of valve repair and subsequent hospitalization. This approach does require the assembly and training of a consistent team of anesthesia, surgical, nursing, and perfusion personnel and might not be applicable to all cardiac surgical programs.

Conclusions

Robotic instrumentation provides a safe and effective vision and instrument platform at the mitral valve when used through a lateral right chest endoscopic approach. This configuration of the robotic system allows 2 surgical personnel to participate actively in instrumentation of the mitral valve structures and might promote higher rates of valve repair in selected patients.

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