Minimally invasive mitral valve surgery began in the mid-1990s with the introduction of the Heart Port Endo CPB system (Heartport Inc., Redwood City, CA). Despite a significant learning curve, this provided a usable platform for remote access cardiopulmonary bypass. Difficulties performing complex mitral valve repair with two-dimensional vision and long-shafted instruments made adoption slow and mostly limited to a few centers. The development of robotics in the late 1990s provided enhancements that promised to overcome the limitations of previous minimally invasive techniques. The most important improvements were three-dimensional vision with magnification of the operative site, and articulated wristed instruments with the articulating portion being down at the level of the valve. Early feasibility was shown by Falk and coworkers in Europe. In the United States robotic-assisted mitral valve repair was pioneered by Chitwood and coworkers and FDA clearance was obtained in December 2002 based on their multicenter trial. Over the next several years we and others modified the technique of robotic mitral valve repair to further take advantage of the system's capabilities, moving away from a rib-spreading anterior mini-thoracotomy and toward a more lateral totally endoscopic approach. Our current technique, utilizing the da Vinci S System (Intuitive Surgical Inc., Sunnyvale, CA), is a totally endoscopic lateral approach. Incisions are made for the robotic instrument and camera ports and the assistant's “working port” is only a 15-mm soft rubber Thoracoport (Ethicon Endo-Surgery Inc., Cincinnati, OH). We use femoral–femoral bypass and a transthoracic “Chitwood” aortic cross-clamp (Scanlon International Inc., St. Paul, MN) placed via a stab wound in the chest. Excellent results are also obtained using endo-balloon aortic occlusion (CardioVations, Ethicon Inc., Piscataway, NJ), although this requires additional teamwork and learning curve.

Virtually any mitral valve pathologic problem can be addressed via an endoscopic robotic approach. The relative contraindications are previous right chest surgery, obesity, severe mitral annular calcification, and severe aorto-iliac disease (although even the latter has been managed on occasion by axillary artery perfusion). Robotic heart surgery is a team process requiring coordination with anesthesiologists, operating room staff, perfusion, and, especially, the patient-side surgeon/assistant. Even mundane tasks such as passing sutures and instruments and maintaining tension on running sutures requires coordination and teamwork between the console and patient-side surgeons. Early in a team's experience it is prudent to select relatively ideal patients who are younger, not obese, and have straightforward mitral valve pathologic problems with a high likelihood of successful repair. As experience grows and operative times improve, more complicated valves and patients can be approached.

Robotic mitral valve repair involves the combination of several technologies and techniques—minimally invasive cardiopulmonary bypass and cardiac arrest, the use of the da Vinci robotic telemanipulation system, coordination between team members, and the mitral valve repair techniques themselves. Once the mitral valve is exposed, virtually all valve repair techniques can be performed robotically. The only repair technique that is fairly unique to the robotic approach is the use of Nitinol U-clips (Medtronic Inc., Minneapolis, MN) in place of flexible annuloplasty bands.

Over the past 4 years, we have performed 160 robotic mitral valve repair operations (18 planned mitral valve replacements were also performed). There were no conversions from robotic to open procedures. Of the 160 patients for whom repair was planned, only one patient was converted to a replacement, whereas all others had successful repair with either 0 or Trace mitral regurgitation at the conclusion of surgery. There have been no operative deaths in this group of patients and average hospital length of stay was 3.7 days (>50% discharged on postoperative day 2 or 3).

Classic quadrangular resection and annuloplasty was the most common repair performed (50%), whereas sliding leaflet reconstruction (25%), anterior leaflet reconstruction usually with Gore-Tex suture (W.L. Gore & Assoc. Inc., Flagstaff, AZ) neo-chordae (16%), and rigid ring remodeling annuloplasty (10%) were performed as well. Concomitant procedures included patent foramen ovale closure in 28 patients, patch closure of atrial septal defect in 3 patients, and Cryo-MAZE procedure in 15 patients. We now close the left atrial appendage routinely in virtually all patients undergoing robotic mitral valve repair.

The steps of robotic mitral valve repair are as follows:

1. Anesthesia setup. Placement of double lumen endotracheal tube, transesophageal echo probe and retrograde...
coronary sinus cardioplegia, and pulmonary artery vent catheters (CardioVations Inc., Ethicon Inc.).

2. Port placement.
3. Cannulation.
4. Docking of robot, introduction of instruments, and exposure of the mitral valve.
5. Mitral valve repair.

In this article the steps and techniques of robotic mitral valve repair are illustrated. It is not our intention to recommend a particular technique for the actual mitral valve repair per se but rather to illustrate that with careful planning and teamwork it is possible to routinely access and reliably repair the mitral valve via a totally endoscopic robotic approach. Mitral valve replacement requires careful suture management by the patient-side surgeon/assistant, but the technique is otherwise very similar. It should be noted that, with minor variation, these techniques can be used to perform other open heart atrial procedures such as atrial septal defect closure, resection of atrial myxoma, stand-alone atrial fibrillation procedures, and tricuspid valve repair.
Operative Technique

Figure 1 Lines, positioning, and cannulation. Patient is intubated with a double lumen endotracheal tube. Transesophageal echo (TEE) probe is placed. Pulmonary artery vent and retrograde coronary sinus cardioplegia catheters (CardioVations, Ethicon Inc.) are placed via the right internal jugular vein. These are positioned with TEE guidance and fluoroscopy with contrast injection is used to confirm good position of the cardioplegia catheter in the coronary sinus.

The patient is positioned at the right edge of the operating room table with a transverse roll under the chest and the arm OFF the table supported in a sling. The table is rotated 15° to the left and placed in reverse Trendelenberg (to lower the hips and gain extra clearance for the right instrument arm of the robot).

Right femoral artery and vein are exposed via an oblique incision just above the groin crease. A purse-string suture is placed in the anterior surface of the vein and, using the Seldinger technique and TEE guidance, a guidewire is passed through the right atrium and into the superior vena cava (SVC). Seeing the guidewire pass up into the SVC is very important to ensure the proper positioning of the venous cannula. A 25-Fr CardioVations “Quickdraw” venous cannula is passed over the wire and positioned so that the tip is several centimeters up the SVC and multiple side holes remain in the right atrium. The femoral artery is cannulated via a transverse arteriotomy, which is later repaired by direct suture closure. ET = endotracheal, PA = pulmonary artery.
Port placement. Port placement is generally done simultaneously with femoral vessel exposure. Local anesthetic is used at all port sites to aid with postoperative pain control. The endoscope camera port is placed in the 4th intercostal space (ICS) 2 to 3 cm lateral to the nipple. In female patients, the incision is placed in the infra-mammary crease and the breast is retracted superiorly to try to enter the chest in the 4th or 5th ICS. CO₂ is insufflated into the chest and the camera is introduced to assure proper location, assess adhesions, and assess the possible need for a diaphragm retraction stitch.

The working port incision (for a 15-mm soft rubber port) is placed in the same interspace, ~4 cm lateral to the camera port. With a finger in the chest via the working port incision for palpation, ports are placed for the left and right instrument arms. The left port is placed one interspace above and approximately halfway between the shoulder and the camera port. The right port is two or three interspaces below and near the anterior axillary line.

A Chitwood transthoracic cross-clamp and a small suction catheter are placed via a stab wound in the axilla. An angiocatheter, which can accommodate the “crochet hook” for suture retrieval, is placed in the mid-axillary line for posterior pericardial traction sutures.

Using the endoscope for visualization, another angiocatheter is placed medially (avoiding the mammary vessels) roughly overlying the aorta. The 4th robotic port for the atrial retractor instrument is placed in the 5th ICS medial to the camera port.

(Inset) The da Vinci robot is “docked” with the patient, the arms are connected to the ports, and camera and instruments are introduced into the chest.
The patient is placed on cardiopulmonary bypass; the heart is decompressed and ventilation is discontinued. This eliminates respiratory movement and creates more "working space."

The pericardium is opened with electrocautery well anterior to the phrenic nerve. The pericardiotomy extends from near the inferior vena cava (IVC) to up over the ascending aorta. Two traction sutures are placed on the posterior pericardial edge and brought out through the posterior angiocatheter to expose the site of left atriotomy. A traction stitch on the anterior pericardium facilitates aortic exposure.

The site of planned atriotomy is prepared with electrocautery and the space behind the IVC is opened. n. = nerve; RAA = right atrial appendage; RIPV = right inferior pulmonary vein; RPA = right pulmonary artery; RSPV = right superior pulmonary vein; SVC = superior vena cava.
Figure 4 Aortic occlusion and cardioplegia. The Chitwood clamp is placed across the aorta. Exposure is provided by the console surgeon to provide a good view into the transverse sinus to assure no injury to the pulmonary artery (PA) or left atrium (LA) appendage.

A long 14-g angiocatheter (with a small side hole cut in it) is placed through the chest wall by the patient-side assistant and then introduced into the aortic root by the console surgeon and held in place while the assistant connects it to the cardioplegia delivery system.

The aorta is then cross-clamped and cardioplegia is delivered antegrade. Additional retrograde cardioplegia may be delivered as well. We routinely administer retrograde cardioplegia at ~20-minute intervals but will give multiple antegrade doses if we have been unable to place the coronary sinus catheter.
Figure 5 Atriotomy and valve exposure. Left atriotomy incision is made anterior to the right pulmonary veins. The Intuitive Surgical Endowrist Atrial Retractor is positioned to elevate the atrial septum and provide exposure. Because of the lateral approach, the amount of retraction required is reduced, causing less distortion of the valve. The atrial retractor position can be adjusted by the console surgeon as needed to optimize exposure for patent foramen ovale closure, closure of the left atrium (LA) appendage, or exposure of the mitral valve. The small suction catheter is positioned in the left pulmonary veins to provide a blood-free field.

We routinely close the LA appendage with a two-layer closure of running 4-0 Gore-Tex. The suture is “followed” by the assistant, via the working port, using a suture hook (ATS Medical Inc., Minneapolis, MN) to pull up the loops for traction. Long sutures (48 inches) facilitate following the suture via a port since the loop is pulled out of the port to be manually held by the assistant. LIPV = left inferior pulmonary vein; MV = mitral valve.
Figure 6  Mitral valve repair—“classic” quadrangular resection. (A) The mitral valve is exposed and evaluated. The assistant uses a sucker to help provide exposure. A robotic valve hook is used to evaluate the leaflets, chordae, etc. Any type of valve repair can be performed robotically. The most frequent repair in our experience is a “classic” P-2 quadrangular resection, plication of the annulus, and reapproximation of the remaining posterior leaflet. (B) The leaflet is excised with a curved scissor. Resano forceps are fairly atraumatic for grasping the leaflets.
Figure 6  (Continued) (C) Felt pledget-reinforced 2-0 Ticron (Covidien, Norwalk, CT) mattress suture is used to plicate the annulus and tied by the assistant with a knot-pusher (or can be tied by the console surgeon using robotic instruments). (D) The remaining P-1 and P-3 leaflets are sutured together with two layers of running 4-0 Prolene (Ethicon Inc, Johnson & Johnson Co, Somerville, NJ) suture, which can be run over the annular plication for additional reinforcement. (Alternatively, interrupted sutures or interrupted nitinol U-clips may be used). Again, we usually have the assistant tie the suture with a knot-pusher.
Figure 7 Sliding leaflet repair. Other repair techniques are frequently used including sliding leaflet repair. (A, B) A quadrangular resection of P2 leaflet is performed. Excessively tall posterior leaflet is separated from the annulus and, if necessary, some of the leaflet base can be resected to further reduce its height. The leaflet is then brought centrally, “sliding” it over, to meet the other leaflet components. At times P-1 and P-3 may both require height reduction, although frequently (as illustrated here) P-1 is less abnormal than P-3. (C) The leaflet base is reattached to the annulus with two layers of running 4-0 Prolene and again the leaflet-to-leaflet attachment is also performed with running Prolene.
Figure 8 Gore-Tex neo-chordae to anterior leaflet. Gore-Tex neo-chordae placement is greatly facilitated by a robotic approach due to the excellent exposure and magnified view of the subvalvular apparatus. The minimal distortion of the valve provided by the lateral approach enhances the ability to judge and adjust chordae length. (A) 4-0 Gore-Tex, buttressed with a pledget, is placed through the head of the papillary muscle. Both ends of the suture are then brought through the leading edge of the leaflet taking two “bites” with each end of the suture. (B) The suture length is then adjusted and the suture is held with a robotic instrument while the assistant ties the suture. Firmly holding the suture and having the assistant tie against the robotic instrument prevent the knot from slipping and making the new chordae too short. MV = mitral valve.
We use flexible silastic sizers that can easily be passed through the 15-mm working port. (The usual rigid sizers would require a larger working port.) A flexible annuloplasty band is placed using Medtronic V-100D U-clips. Rigid or semi-rigid bands and rings can be placed robotically but (at least currently) require standard sutures and tying.

The band is first secured at the two trigones and then additional suture-clips are placed on either side working toward the center of the band so that it is evenly spaced along the annulus. A “bite” is taken into the annulus with one end of the U-clip and then both needles are passed through the band. When released, the clips securely hold the band in place. To provide a little more mobility of the band and facilitate the passage of the needle into the annulus, the nearest end of the previous clip is left un-released until the next clip is in place. Two needle holders are used to allow passage of the needles and release of the clips with either hand.

Figure 9  Annuloplasty ring. We use flexible silastic sizers that can easily be passed through the 15-mm working port. (The usual rigid sizers would require a larger working port.) A flexible annuloplasty band is placed using Medtronic V-100D U-clips. Rigid or semi-rigid bands and rings can be placed robotically but (at least currently) require standard sutures and tying.

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Figure 10  **Atrial closure.** Once the repair is complete, the left atriotomy is closed with running 4-0 Gore-Tex, beginning a suture at each end of the atriotomy and meeting in the middle. The heart is allowed to fill and de-air via the atriotomy before tying the suture.
Figure 11 Removing the cross-clamp and the cardioplegia catheter. Suction is placed on the aortic cardioplegia catheter for further air protection and the aortic cross-clamp is removed. Once the heart is beating well (and preliminary evaluation of the repair by TEE looks good), the angiocatheter is removed from the aorta (Ao) and the puncture site closed with a pledget-reinforced 4-0 Gore-Tex mattress suture.
References

Figure 12 Final steps. A 19-Fr Blake drain (Ethicon Inc, Johnson & Johnson Co) is brought into the chest via the atrial retractor port and placed behind the IVC into the posterior pericardium. The pericardium is loosely closed with two sutures. An additional Blake drain is placed via the right instrument port into the pleural space.

The instruments and ports are all removed and both lungs are ventilated. The patient is then separated from cardiopulmonary bypass and the repair is evaluated by TEE. While Protamine is administered, the cannulas are removed, the purse-string in the femoral vein is tied, and the femoral arteriotomy is repaired.

After Protamine is administered, the right lung is deflated and the endoscope (handheld) is reintroduced into the chest to examine the aortic cardioplegia site, as well as ALL port and angiocatheter sites to assure good hemostasis. Cautery may be used and in rare instances the robot may need to be redocked to control chest wall bleeding sites.

On-Q catheters (I-Flow Corp, Lake Forest, CA) are placed along the interspace with the camera and working ports to aid postoperative pain relief. All incisions are closed with absorbable sutures and Dermabond glue (Ethicon Inc, Johnson & Johnson Co).