Perspective

# Robotic mitral valve surgery—current status and future directions

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Robotic mitral valve surgery is the most common robotic cardiac procedure performed today. Benefits include smaller, less invasive incisions resulting in less pain, shorter length of hospital stay, improved cosmesis, quicker return to preoperative level of functional activity, and decreased blood transfusion requirements. The history and evolution of robotic mitral valve surgery is detailed in this article. Our institution has performed over 800 robotic mitral valve surgeries, and our technique and outcomes are described. Outcomes and operative times are similar to that for sternotomy and minimally invasive approaches to mitral valve surgery. The benefits and limitations of robotic mitral valve surgery are compared with conventional approaches, and future directions are also discussed.

**Keywords:** Robotic surgery; robotic cardiac surgery; mitral valve surgery; mitral valve repair; minimally invasive cardiac surgery

Submitted Sep 20, 2013. Accepted for publication Oct 10, 2013.
doi: 10.3978/j.issn.2225-319X.2013.10.04
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## Introduction

Since the first robotic mitral valve repair, performed by Carpentier in 1998 using an early prototype of the da Vinci™ surgical system (Intuitive Surgical, Inc., Sunnyvale, CA) (1), robotic mitral valve surgery has become an accepted operation. Robotic mitral valve surgery evolved from minimally invasive mitral procedures, and thus shares the same benefits of smaller, less invasive incisions resulting in less pain, shorter length of hospital stay, improved cosmesis, and quicker return to preoperative level of functional activity. Minimally invasive mitral valve surgery began by using a right anterolateral thoracotomy approach. Further advances in instrumentation, visualization and techniques were developed to enable peripheral cannulation, myocardial protection, and improved exposure. Minimally invasive mitral repairs are now commonly performed using endoscopic camera visualization and endoscopic instruments. These approaches have become the standard of care at many institutions, and excellent results have been achieved.

As minimally invasive cardiac operations gained favor, developments in tele-manipulation technology and optics led to the evolution of robotic-assisted cardiac surgery. Currently, the da Vinci™ surgical system is the only Food and Drug Administration (FDA) approved robotic system used for cardiac surgical procedures. In the modern operating theater, robotic heart surgeons use this system to perform complex mitral valve repair, coronary revascularization, atrial fibrillation ablation, intra-cardiac tumor resection, atrial septal defect closure, and left ventricular lead implantation.

## Brief history of minimally invasive mitral surgery

As for other less invasive cardiac operations, minimally invasive and subsequently robotic mitral valve surgery evolved from modifications of incisions previously carried out under direct vision. Large series from Cohn and Cosgrove showed that mitral surgery, performed via minimal access incisions and under direct vision, offered comparable results to the sternotomy approach, with mortality rates ranging from 1-3% (2,3). The next step forward was to perform mitral surgery using videoscopic assistance. The first mitral repair using a videoscope was performed by Carpentier in

1996 (4), and the first mitral valve replacement was done by Chitwood later that year (5). The experience by the Leipzig Heart Center was reported by Mohr in 1998 and showed excellent results in fifty-one patients who underwent simple mitral repair or replacement operations (6). At the same meeting, Chitwood reported a thirty day operative mortality of 3.2% with no major complications in thirty-one patients. This series consisted of a variety of complex repairs, including quadrangular resections, sliding valvuloplasties, and chordal replacements (7).

## History of robotic mitral surgery

The most common robotic cardiac procedure performed to date is mitral valve repair or replacement. The first robotic mitral repair was performed by Carpentier in 1998, using an early prototype of the da Vinci™ Surgical System (1). The following week, Mohr repaired five mitral valves and performed a coronary revascularization with the device (8). The first robotic mitral repair in North America was performed by Chitwood in 2000, and consisted of a large $P_2$ trapezoidal resection with an intra-corporeal suture repair followed by annuloplasty band implantation (9). Two subsequent FDA investigational device clinical trials led to approval of the da Vinci™ surgical system in 2002 for mitral valve surgery in the United States (10,11).

Mihaljevic *et al*. reported their results of 261 mitral valve repairs done robotically between 2006 and 2009 (12), which were compared with mitral valve repairs done via complete sternotomy (n=114), partial sternotomy (n=270), and right mini-anterolateral thoracotomy (n=114). Outcomes were compared on an intent-to-treat basis using propensity-score matching. Median cardiopulmonary bypass time was 42 minutes longer for robotic than for complete sternotomy, 39 minutes longer than partial sternotomy, and 11 minutes longer than right mini-anterolateral thoracotomy (P<0.0001). There were no in-hospital deaths in any group, and neurologic, pulmonary, and renal complications were similar among groups. The robotic group had the lowest occurrences of atrial fibrillation and pleural effusion, contributing to the shortest hospital stay (median 4.2 days), and 1.0, 1.6, and 0.9 days shorter than for complete sternotomy, partial sternotomy, and right mini-anterolateral thoracotomy (all P<0.001), respectively.

Similar reductions in length of stay were seen at the University of Pennsylvania in a comparison of 39 patients who underwent sternotomy and mitral valve repair or replacement with 26 patients who underwent robotically assisted mitral valve repair or replacement (13). Patients who underwent robotic-assisted surgery experienced shorter mean duration of post-operative hospitalization (7.1 versus 10.6 days; P=0.04), despite longer cross-clamp and bypass times (110 versus 151 minutes; P=0.0015; 162 versus 239 minutes; P=0.001, respectively). Mean packed red blood cell transfusion was also lower among patients who underwent robotic-assisted mitral valve surgery (2.8 versus 5.0 units; P=0.04).

Our institution has performed over 800 robotic mitral valve repairs, including over 40 in patients who have had a prior cardiac operation. Results have been published for the first 540 patients (14), including 454 patients who underwent a lone mitral repair, and 86 who had a concomitant atrial fibrillation ablation. The average cross clamp and cardiopulmonary bypass times were 116 and 153 minutes respectively in the lone mitral repair patients. The group operative mortality was 0.4%, while the mean follow-up period was 351 days (15-946 days), and 2.9% of patients required a re-operation for a failed repair. The arrest and cardiopulmonary bypass times have improved with ongoing experience. In the first FDA trial, the average cross clamp time was 150 minutes (10), however, in the second multi-center FDA trial, the average cross clamp time fell to 126 minutes, with little variation in operative time between centers (11). We now use the Cor-Knot device (LSI Solutions, Victor, NY) in lieu of intracorporeal knot tying, which has shortened our average cross clamp time to 94.7 min and our average cardiopulmonary bypass time to 144.9 min (P<0.02) (15).

## Description of technique

Patients are intubated with either a double lumen endotracheal tube or a bronchial blocker to allow for right lung isolation, followed by a transesophageal echocardiogram. Topographic valve models are produced from high quality three-dimensional transesophageal echocardiography images, which allows subsequent planning for a successful repair. The patient is positioned with the right side up thirty degrees from horizontal, followed by bicaval venous cannulation, via the right internal jugular and right femoral veins. Right femoral arterial cannulation is usually preferred, however in patients with aorto-iliac disease or small femoral arteries, we cannulate the right axillary artery with a side arm graft cannula.

A 2 to 3 cm working port incision is made in the 4$^{th}$ intercostal space anterior to the anterior axillary line (AAL), to be used as both the working incision and camera access. Alternatively, a 2-cm lateral working port with a separate,

 

more medial, camera port can be employed. Robotic arm trocars are introduced, one in the 5th intercostal space at the AAL for the right arm, one in the 3rd intercostal space anterior to the AAL for the left arm, and the final in the 4th intercostal space, two finger breadths lateral to the mid clavicular line for the dynamic atrial retractor. The da Vinci™ system is then docked. A pericardiotomy is performed, taking care to visualize and preserve the phrenic nerve, and the pericardium is suspended using retraction sutures. A cardioplegia cannula is secured in the anterolateral surface of the ascending aorta just proximal to the fold of Rindfleisch using a 3-0 Goretex™ pursetring suture with pledgets. This cannula serves as an aortic root vent after removing the cross clamp. The ascending aorta is occluded using the Chitwood transthoracic aortic cross clamp (Scanlan International, Minneapolis, MN), and antegrade crystalloid Bretschneider's cold cardioplegia is used to arrest the heart. In re-operative cases and in patients with an atherosclerotic or calcified ascending aorta, hypothermic (26 ℃) fibrillatory arrest is used for myocardial protection.

After arrest, Sondergaard's groove is dissected, and the entry of the pulmonary veins into the left atrium is identified. A left atriotomy is performed and the dynamic atrial retractor is used to expose the mitral valve. The wrist-like robotic instruments allow for complex repair techniques to be employed. Most commonly we use the following techniques: (I) limited triangular or quadrangular resection; (II) folding valvuloplasty; (III) chordal shortening either by translocation or papillary muscle folding; (IV) neochord implantation; and rarely (V) a leaflet sliding-plasty. As previously mentioned, we now use the Cor-Knot™ suture device (LSI Solutions, Victor, NY), to secure annuloplasty bands, rather than tying each knot intracorporeally. After ensuring a competent valve, the atriotomy is closed with a running 3-0 Goretex™ suture.

A bipolar ventricular pacing wire is secured to the posterior surface of the right ventricle, and atrial pacing wires can be affixed to the right atrium. We insert a 24 French Blake drain along the mediastinum, and a 28 French right angle chest tube posterior to the lung. Both drains are tunneled through the chest wall via separate robotic arm trocar incisions, thus avoiding the need for a new incision.

## Benefits/advantages of robotic mitral surgery

The da Vinci™ Surgical System provides increased operative dexterity for surgeons. The wrist-like articulating instruments move with six degrees of freedom, compared with the four degrees of freedom that endoscopic instruments provide. Other benefits include tremor-free movements, ambidexterity, and the avoidance of the fulcrum effect that is inherent when using long-shafted endoscopic instruments. Moreover, the system improves operative visualization greatly through the use of three-dimensional high definition imaging. Visualization of the mitral valve in particular is unparalleled when using the da Vinci™ system compared to minimally invasive or sternotomy approaches.

Smaller incisions lead to decreased operative stress, and the smallest incisions for mitral valve surgery are achieved when using the da Vinci™ system. As we have described, patients benefit from less pain, improved cosmesis, quicker return to recovery, decreased length of stay, and possibly decreased transfusion requirements. Morbidity and mortality rates have been shown to be similar with those for conventional sternotomy and minimally invasive approaches.

## Limitations/disadvantages

Success is predicated upon identification of appropriately skilled team members. Moreover, patient selection is paramount for success in robotic heart surgery. Relative contraindications to a robotic approach include extensive pleural adhesions, poor pulmonary function, poor ventricular function, aortic regurgitation, and pectus excavatum. Many surgeons prefer the traditional sternotomy in high risk patients with comorbidities such as poor left ventricular function, given increased operative times associated with robotic surgery historically. However, we have shown that in experienced centers with refined techniques and skilled robotic teams, operative times are comparable with those for sternotomy, with the added benefit of no increased risk and shortened length of stay. Improvements in technology and instruments will continue to improve operative times for robotic surgery. While we have had success in patients with poor ventricular function, likely owing to the overall decrease in operative stress when compared with sternotomy, we still prefer the sternotomy approach in patients with severe pulmonary disease or pulmonary hypertension.

Many surgeons have also remained concerned about the lack of haptic feedback. Robotic surgeons have become familiar with "ocular tactility", relying on visual tissue deformation to judge the amount of force being applied to tissues. In our experience, the lack of haptic feedback has not been a problem. Future robotic systems will likely incorporate strain sensors to the instrument arms, allowing

 

for haptic feedback and precise control of force.

## Future directions

Instrument and camera sizes will decrease, and optics will improve, allowing for smaller incisions. A greater variety of robotic instruments will be developed, allowing for more operative options and improved dexterity. Advances in three dimensional echocardiography and modeling software will continue to be made, possibly allowing a "blueprint" model to be overlaid on the operative field image at the console.

It has become evident that in order to achieve success as a robotic cardiac surgery program, several key elements are required. Firstly, the concept of a highly specialized and trained robotic team is paramount, and includes anesthesiologists, perfusionists, operating room staff, nurses, and surgeons. Due to the limited visualization and access to the entire heart through minimal access incisions, skilled echocardiographers are crucial. Achieving safe cannulation, planning for complex valve repairs, and monitoring cardiac function are all predicated on high quality, three-dimensional transesophageal echocardiography. Finally, robotic heart surgery centers must have an adequate referral base to attain safety and efficiency. To date, several centers have achieved success in robotic cardiac surgery, performing a variety of heart operations reproducibly, reliably, effectively, and safely. We are confident that this promising technology will continue to advance and become increasingly utilized worldwide.

## Acknowledgements

Drs. Chitwood and Nifong are on the speaker's bureau for Intuitive Surgical. Honoraria only.
*Disclosure:* The authors declare no conflict of interest.

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**Cite this article as:** Bush B, Nifong LW, Alwair H, Chitwood WR Jr. Robotic mitral valve surgery—current status and future directions. Ann Cardiothorac Surg 2013;2(6):814-817. doi: 10.3978/j.issn.2225-319X.2013.10.04

 