Robotic-assisted cardiac surgery: an overview

AU Gullu*, S Senay, C Alhan

Abstract

Introduction

Robotic applications in cardiac surgery now include mitral and tricuspid valve operations, coronary artery bypass grafting, atrial fibrillation ablation, intracardiac tumour resection and congenital heart surgery, such as atrial septal defect closure. In this article, we will review our experience in each robotic cardiac procedure, the published evidences of benefits and assess the limitations. We will also discuss future directions in this rapidly evolving field.

Mitral valve repair or replacement

Operating theatre should be large enough for a robotic programme in cardiac surgery to fit all devices including surgeon console, patient side cart, transesophageal echocardiography (TEE) and cardiopulmonary bypass (CPB) machine. Figure 1 shows our routine operating room set up for mitral valve repair or replacement.

Anaesthetic set-up

A peripheral IV cannula and a radial or brachial arterial line are placed. If using EndoBalloon, bilateral radial arterial cannula is mandatory. Intubation is achieved with double lumen endotracheal tube. TEE probe and a Foley catheter are placed. Central venous and the other cannulation sites are marked and the diameters of the vessels are measured by the aid of ultrasound. After sterile preparation, a central venous line is inserted via left internal jugular vein. A 17 F venous cannula is inserted for venous drainage via right internal jugular vein with TEE guidance (Figure 2). Defibrillator pads are placed properly.

Preparation and monitoring

The right chest of the patient is aligned with the edge of OR table. The right arm is hanged down in a towel-sling alongside the patient below the table level for maximal exposure of right chest. A positioning roll is placed under the right scapula to lift right hemi-thorax and drop shoulder, which also helps spreading the intercostal spaces. Operating table is rotated 15° to the left to raise the right side of the patient. Both the head and the leg boards of the operating table rest one step down (Figure 3). The planned incisions can be marked on right side of thorax (Figure 4). After sterile preparation...
and draping, the right femoral vessels are accessed through a 2-cm oblique incision along the inguinal crease. Systemic heparin is given (300 IU/kg) to achieve ACT > 400 s. Both the right femoral artery and vein are cannulated with appropriate sized cannulas according to measurements of ultrasound. The tip of the femoral vein cannula is placed at the junction between right atrium and inferior vena cava (IVC) under TEE guidance. Some groups cannulate and heparinise the patient following the port placement to avoid the traumatic bleeding related to earlier anticoagulation.

An appropriate port placement is one of the most critical steps in the operation. Otherwise, the collisions of the robotic arms or insufficient working space in right chest may cause a technical challenge through the operation. A 2-cm incision is made on the 4th ICS, 1–2 cm medial to the anterior axillary line in male or just below the inframammary fold in female. After deflating the right lung, a 20-mm working port is placed through this incision. A 3–4-cm incision is necessary for mitral valve replacement to allow the prosthetic valve to be introduced through the incision. In this case, a small size soft tissue retractor (Alexis Rancho Santa Margarita, CA, USA) is used. The use of a rib spreader must not be used to avoid postoperative pain. A 30° endoscope is inserted to scan the right thorax. While facing the right pulmonary veins, the angle of the endoscope shaft must be 0° (perpendicular to the thoracic wall). Otherwise, it may be necessary to move one ICS up to get the best camera angle. All instrument port placements are guided by endoscopic vision and left index finger inserted through the working port. A 10-mm camera port is introduced through the same ICS, 6–7 cm (4 finger breadth) medial to the working port. In mitral valve replacement, an additional camera port is not necessary because the

**Figure 1:** Operating room set up for robotic-assisted mitral valve repair or replacement.

**Figure 2:** Venous cannula insertion for venous drainage via right internal jugular vein with transesophageal echocardiography guidance.

**Figure 3:** The position of the patient on the operating table.
The planned incisions marked on right side of thorax.

Camera is introduced through the working port. The right instrument arm port is created at 5th or 6th ICS on the anterior axillary line caudal of camera port again keeping a 6–7 cm distance with camera port. The left instrument arm port is created at 3rd ICS and 2–3 cm medial of the anterior axillary line paying attention to leave a 6–7 cm distance with the other ports. One more small incision is made in the 2nd or 3rd ICS on the mid-axillary line to insert aortic cross clamp and left atrial sump. Instead some groups apply another system which is applied via femoral artery under TEE guidance relies on a specifically designed tri-lumen catheter called the EndoBalloon to achieve aortic clamping, cardioplegia delivery, or aortic root venting and aortic root pressure monitoring. However, we do not prefer this system which has the risks of malposition and aortic dissection during the procedure and also increase the cost. Finally, atrial retractor port is placed one ICS below camera port para-sternally taking care not to injure the right internal mammalian artery. Here, we use a port with a side hole for CO₂. CO₂ line is attached to this port with a pressure of 6–8 mmHg. Apart from the use of single lung ventilation, CO₂ is insufflated into the hemithorax through the side being operated upon to prevent smoke formation and hazard of gas explosion in the hemithorax. It should be kept in mind that CO₂ pressure above 5–10 mmHg, may lead to a reduction in venous return to the heart and result in increased arterial CO₂ tension especially in totally closed procedures (LIMA harvesting, etc.).

Before placing any stay sutures, two angiocaths are preloaded with suture snares to speed up suture passing, which is time consuming. 14 GA angiocath catheters are inserted through the intercostals spaces in the anterior axillary line or mid-axillary line for the retrieval of traction sutures to the diaphragm (6th ICS) and pericardium (1× 4th/5th ICS, 1× 3rd/4th ICS).

Then the da Vinci Patient Cart is rolled in at a 0–30° angle to accommodate for the natural position of mitral valve. The centre column should be lined up with the camera port in the right chest. Next, the camera arm and the other instrument arms are docked (Figures 5 and 6). Once the patient cart is docked to the patient, the operating table should not be moved anymore. At this point in the setup, the surgeon can take responsibility for clutching and positioning the camera and the arms. If a traction suture to the diaphragm is needed, a needle driver is used as right instrument and Resano forceps is used as left instrument.

Continuous pumping just before the pericardiotomy deflates the heart inside the pericardium and as the ventilation of the left lung is stopped the intrathoracic space increases. This prolongs the pump time slightly, but facilitates pericardiotomy, placement of stay sutures as well as the following procedure steps. For pericardiotomy the right instrument is switched to spatula. Following pericardiotomy, stay sutures (2.0, Ticron) are placed and passed through the crochet hook which is passed through the angiocath, it is advanced to trap the sutures, then hook and angiocath are withdrawn simultaneously. The sutures are slightly pulled and tied to skin over a piece of small tubing set, and it is repeated for the other pericardial or diaphragmatic traction sutures.

Cross clamp is passed through second intercostal space in mid-axillary line and aorta is clamped. The shaft of the Chitwood clamp should be cranial to the vena cava superior-right atrial junction. Single shot cold cardioplegic solution is induced with 15 mL/kg (~4 °C; Custodiol®, Dr. F. Köhler Chemie, Alsbach, Germany) via holder driven 16 GA air aspirator needle through working port for a period of 6–8 min. This single dose is generally enough to persist myocardial electromechanical inactivity till declamping of the aorta (up to 3 h). If the right side of the heart is planned to be open for tricuspid valve intervention, caval veins are encircled and snared. Instate of encircling, endoscopic bulldog clamps may be applied onto the distal ends of both Superior Vena Cava (SVC) and Inferior Vena Cava (IVC) to facilitate the total occlusion of caval veins by the aid of an applicator (Aesculap, Braun, Germany) through the service port. As long as the cardioplegic infusion stops, the needle is withdrawn and left atriotomy is done.

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The valve and the subvalvular apparatus can be analysed robotically by the aim of hooks. However, it saves time to decide what to do before the operation based on especially 3D TEE examination. Left instrument may be changed to Resano forceps for a traumatic handling of the valve tissue. For cutting a leaflet tissue, curved scissors may be used. For a single stitch, console surgeon hands the needle back to the assistant surgeon. For both mitral annuloplasty and replacement, 2.0 Ticron sutures are passed through annulus robotically then placed to colored and numbered suture holder one by one in a routine fashion by the assistant surgeon. All the sutures are passed through the sewing ring of the prosthesis (annular ring or prosthetic valve), and the prosthesis is glided down into the native annulus (Figures 7 and 8). The valve/ring handle is released. The knots can be tied by console surgeon or via knot-pusher by the assistant surgeon (Figures 9 and 10). Automated knotting is another option (The Cor-Knot™, LSI Solutions, Inc., Victor, NY) which uses a titanium clip to secure sutures, eliminating intra-cardiac knot tying and reducing operative times. The replaced or repaired valve is tested and left atriotomy is closed usually with polytetrafluoroethylene sutures, which are preferred for atrial closure during robotic surgery thanks to their greater breaking strength.
strength. Leyla loop can also be prepared at operating table and can be applied at both the ends of atriotomy to save time.

If the tricuspid valve intervention had been performed with use of bulldog clamps, the clamps are removed with the applicator or the snares are released. A 4.0 Prolene suture is placed to the hole of cardioplegia needle and the needle is inserted. Following the deairing manoeuvres the aortic cross clamp is removed.

After controlling bleeding, the robotic arms are removed from the chest and double lung ventilation is initiated. CPB is terminated following hemodynamic stability and routine TEE control. The peripheral cannulas are removed. Protamine is administered. Finally, in a very short period of single lung ventilation control for bleeding especially for ports is done with a variable direction view endoscopic camera (Endocameleon, Storz, Tuttingen, Germany). A small flexible drainage tube is placed in the pericardium and one or two conventional chest tubes are placed in the right pleural space, all through existing port incisions. All incisions are closed in layers with absorbable suture material. Figure 11 shows the view of incisions 2 months postoperatively.

Figure 7: Patient side surgeon playing an important role during the robotic surgery.

Figure 8: The view of incisions just after the robotic-assisted mitral valve replacement.

Figure 9: Implanted prosthetic biological valve.

Figure 10: Implanted mechanical valve.

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Coronary artery bypass grafting

For CABG, robotic system is used to harvest the left internal mammarian artery (LIMA) in our routine practice. LIMA-coronary anastomosis is hand-sewn via mini thoracotomy on beating heart. For robot-assisted CABG, the patient is placed in a supine position with a roll placed between the left scapula and spine to lift the left thorax. The operating table is rotated 10–15° to raise the patient’s left side. The patient is draped to allow easily access in case of femoral cannulation or saphenous vein harvesting. The camera port is placed in the 5th intercostal space, 2 cm medial of anterior axillary line. A 30° angled camera is inserted and the thoracic cavity is scanned to exclude the presence of adhesions and to observe anatomical landmarks. After single right-lung ventilation is initiated and CO₂-insufflation (in the range of 10–12 mmHg) is begun for clear visualisation. Under direct vision of the camera, the right instrument port is placed in the 3rd intercostal space and the left instrument port is placed in the 7th intercostal space, both medial to the anterior axillary line. The anatomic landmarks, such as the phrenic nerve and the subclavian artery are identified with the camera.

LIMA harvesting is achieved robotically via a low power monopolar cautery and micro forceps. The following steps of harvesting are in a routine fashion. The pedicle is not detached from the chest wall until the anastomosis is finally performed to avoid torsion of the graft. An intercostal incision. (4–5 cm) in the 4th ICS for male patients and inframammary for females, is made. Intercostal muscles are divided and a soft tissue retractor is placed to maximise access. The pericardium is opened down to the diaphragm and then towards the right pleura. Heparinisation with the target of ACT:300 s is done. Myocardial stabilisation is accomplished using stabilisers (Figure 12) which is placed through the subxyphoid port. Vacuum lines and irrigating saline line are connected and advanced into the field of view. LIMA is cut and spatulated in the preparation of anastomosis. Proximal LAD occlusion is achieved with temporary silastic occlusion tapes. Using a 15° sharp blade the arteriotomy is performed and enlarged with Potts scissors. The LAD-Lima anastomosis is performed under direct vision with 8-0 polypropylene running suture. The occlusion tapes and the vascular clamp are released and the left lung is ventilated. After pleural drainage tube is placed, the stabiliser and instruments are withdrawn and the left lung is ventilated. Figure 13 shows the view of incisions at 2 months postoperatively.

Repair of atrial septal defect

The preparation, monitoring and positioning for robotic ASD repair is...
Similar to robotic mitral or tricuspid valve procedures. Following the initiation of CPB, a piece of pericardium is prepared and placed in glutaraldehyde solution for initial fixation. A 0° endoscope may be used for sinus venous defects for a better exposure. The defect can be repaired primarily or with a pericardium using Resano forceps and needle driver.

**Discussion**

The authors have referenced some of their own studies in this review. These referenced studies have been conducted in accordance with the Declaration of Helsinki (1964) and the protocols of these studies have been approved by the relevant ethics committees related to the institution in which they were performed. All human subjects, in these referenced studies, gave informed consent to participate in these studies.

Today, there is no doubt that operating through smaller incision results in decreased postoperative pain, length of intensive care-hospital stay, transfusion requirements and risk of infection. Minimally invasive surgery works well especially in some types of operations, such as for gallbladder and knee where the part of the body to be operated upon is motionless. Surgical manoeuvres that need to be performed are relatively simple for these procedures. However, endoscopic surgery has achieved only limited success in more complicated operations such as heart surgery, where the heart is beating and the surgical manoeuvres tend to be complex. Additionally, moving the surgical instruments manually during endoscopic surgery can be difficult and the length of the instruments are longer than normal which necessitates long training period. Long instruments also exaggerate normal hand tremors.

Compared with four degrees of freedom of endoscopic instruments, robotic surgery with da Vinci™ System provides increased operative dexterity for surgeons by the wrist-like articulating instruments move with six degrees of freedom. Other benefit of robotic surgery includes tremor-free movements, ambidexterity and the avoidance of the fulcrum effect that is inherent when using long-shafted endoscopic instruments. Moreover, the system highly improves operative visualisation through the use of three-dimensional high definition imaging.

Mitral valve surgery is the most frequently performed robotic-assisted cardiac surgery. Visualisation of the mitral valve in particular is unparalleled when using the da Vinci™ System compared with mini thoracotomy or sternotomy approaches. This feature provides better exposure of subvalvular apparatus and may increase the possibility of mitral valve repair instead of replacement.

Increased time required to repair or replace the mitral valve resulting in longer CPB and XC time remains one of the major drawbacks of a robotic approach especially at the beginning of programme, but total procedure times decrease significantly as surgical teams become more skilled and gain experience. Mihaljevic et al. in a propensity match cohort comparing robotic surgery with other methods (full sternotomy, partial sternotomy and mini thoracotomy) for mitral repair showed longer operative, perfusion and aortic cross-clamp times. Nevertheless, this increase did not translate to poor outcomes. In fact, a successful mitral repair was obtained in more than 95% of robotic group patients. The hospitalisation time was reduced by almost 1 day in the robotic cohort.

Stepwise progression of robotic technology and procedure development continues to make robotic operations easier and faster. For example, East Carolina University developed a double-arm U-clip made of nitinol alloy which allows a deployed clip to return to its preformed shape to secure a mitral annuloplasty band, and designed to be faster than knot tying to reduce operating times. When compared with sutures for securing mitral annuloplasty band, the U-clips resulted in a shorter total time required to secure the band due to quicker U-clip deployment than knot tying. Recently, again from the same group, Nifong and colleagues presented preliminary results of the novel Cor-Knot device (LSI Solutions, Inc., Victor, NY) which uses a titanium clip to secure sutures and eliminate knot tying. When compared with robotic knot tying, the Cor-Knot significantly reduced time for securing sutures and CPB duration.

In a multicentre phase II, clinical trial of robotic mitral repair; CPB, XC and operative times decreased by 4.3, 3.7 and 4.4 min per case. They found that time began to decrease after the surgeon had performed approximately 15 cases. To date, Nifong et al. reported the largest series of robotic mitral repair (n = 540 patients) and showed 0.4% early and 1.7% late mortality. Postrepair TEE showed 82.8% patients with no mitral insufficiency, 14.8% with trace, 2.2% with mild and 0.6% with moderate mitral insufficiency.

Percutaneous coronary intervention offers a much less invasive treatment option compared with CABG, but the long-term patency rate of the LIMA to LAD graft is now the gold standard for revascularisation.
of the LAD\textsuperscript{14}. Its patency rate can reach as high as 95–98% at 10–20 year follow-up\textsuperscript{16,17}. Following the revascularisation, reintervention is much more than CABG and also it is known that the clinical consequences of stent complications can be far more serious than the complications of graft occlusion\textsuperscript{18–21}. However it may not be easy to convince a patient for a more invasive method. By capitalising on the proven durability and survival advantage associated with LITA–LAD grafting, less-invasive surgical options like minimally invasive direct coronary artery bypass (MIDCAB), robotic-assisted CABG and robotic-assisted totally endoscopic coronary artery bypass (TECAB) can be applied to patients with critical coronary disease. Several surgeons have shown good results on both beating and arrested hearts with totally endoscopic robotic CABG\textsuperscript{22–24}. Furthermore, cardiologists may be more willing to refer patients for this approach providing patients with the best available treatment option (LAD–LIMA).

So far, in our programme we perform off-pump LAD–LIMA grafting via a 4–5 cm anterolateral thoracotomy after robotic LITA harvest and pericardiotomy. In contrast to TECAB, we perform anatomoscopy manually with direct vision in a manner similar to that performed via sternotomy. The main disadvantages of this approach are the inability to graft other major coronary territories. For patients suitable for a hybrid revascularisation strategy, combining percutaneous intervention with stenting of non-LAD lesions with robotic-assisted LAD–LIMA grafting may be another option.

There have been no large, truly randomised comparisons of surgery with transcatheter closure of ASD. The design of such a study may be problematic, because, given a choice between surgery and device closure, parents and patients often prefer the latter method. Longer term follow-up is available just for surgical treatment, even the first transcatheter closure of ASD described by King et al. in 1974\textsuperscript{25}. Chessa et al. have reported on a large series of 417 patients who had catheter closure of secundum ASDs and there were 8.65% major and minor complications. The most common complication was device embolisation/malposition occurring in 3.5% of cases\textsuperscript{26}.

On the other hand, Roos-Hesselink et al. have reported longitudinal follow-up of mean 27 years after surgical closure of secundum ASDs in 135 patients. The median hospital stay was just for 4 days. There was no cardiovascular mortality, stroke, heart failure or pulmonary hypertension. However, symptomatic supraventricular tachyarrhythmias occurred in 6% of patients in the following 15 years. Early complications after surgery include wound infection, pericardial effusions which may cause tamponade\textsuperscript{27}.

Therefore as these series show, the surgical closure is not without risk but it provides closure of the defect under a direct vision instead of two-dimensional fluoroscopy. Using an autologous pericardial patch during open surgery avoids the patient from the risk of embolus/thrombosis of the closure devices. Moreover, irrespective of the size the defect can be closed surgically in contrast to transcatheter technique in which the large size defect is one of the drawbacks.

In an FDA Investigational Device Exemption trial, Argenziano et al. demonstrated that ASD closure in adults can be performed safely and effectively using the da Vinci\textsuperscript{TM} surgical system\textsuperscript{28}. Bonaros et al. also demonstrated no mortality or residual shunt in patients undergoing robot-assisted ASD closures\textsuperscript{29}. As many of these procedures were done in young, physically active patients, the robotically assisted, totally endoscopic approach of ASD closure offers the tangible benefits of decreased pain, sternal stability, less bleeding and wound complications and improved cosmesis\textsuperscript{30}.

### Conclusion

Even still in its infancy, robotic surgery has already proven itself to be of great value. To date, several centres have achieved success in robotic cardiac surgery, performing a variety of heart operations reproducibly, reliably, effectively and safely. However, many topics for discussion still exist such as credentialing, training requirements and licensing. Medico-legal issues are still limiting.

Endoscopes with the feature of variable adjustment of viewing direction are already in the market. Also many improvements such as strain sensors to the instrument arms allowing for tactile feedback and precise control of force are likely to be on the way. The most important and distinctive difference of robotic cardiac surgery compared with other surgical disciplines is the importance of “team work”. It is not possible for a cardiovascular surgeon to succeed in robotic cardiac surgery without cooperation from cardiologists, anaesthesiologists, perfusionists, nurses and even from the hospital management.

We believe that the future of robotic surgery is limited only by our imagination.

### Abbreviations list

- CABG, coronary artery bypass grafting
- CPB, cardiopulmonary bypass
- IVC, inferior vena cava
- LIMA, left internal mammarian artery
- MIDCAB, minimally invasive direct coronary artery bypass
- TECAB, totally endoscopic coronary artery bypass
- TEE, transesophageal echocardiography

### References


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