Updates in Minimally Invasive Cardiac Surgery for General Surgeons

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**KEYWORDS**  
- Minimally invasive cardiac surgery  
- Atrial septal defect  
- Coronary artery bypass graft  
- Mitral valve  
- Robot  

**KEY POINTS**  
- Significant improvement and development have occurred in minimally invasive cardiac surgery over the past 20 years.  
- Although most studies have consistently demonstrated equivalent or improved outcomes compared with conventional cardiac surgery, with significantly shorter recovery times, adoption continues to be limited.  
- In addition, cost data have been inconsistent. Further ongoing trials are needed to help determine the exact roles for these innovative procedures.

**HISTORY OF MINIMALLY INVASIVE CARDIAC SURGERY**  
The era of minimally invasive mitral valve (MV) surgery began in 1948 when Harken and Ellis\(^1\) first described mitral valvulotomy through an intercostal approach. In 1994, Benetti and Ballester\(^2\) from Argentina first described the left internal mammary artery (LIMA) to left anterior descending artery (LAD) anastomosis through a small left anterolateral thoracotomy; this was the first description of minimally invasive direct coronary artery bypass (MIDCAB) and was followed by Subramanian\(^3\) in the United States in 1996. Cosgrove and Sabik\(^4\) first described minimally invasive cardiac procedures in the United States in 1996 for the aortic valve (AV) followed by the MV.\(^5\) Stevens and colleagues\(^6\) invented the heart port platform in 1996, which opened the door to minimally invasive endoaortic cardiopulmonary bypass (CPB). Carpentier and colleagues\(^7\) in 1996 did the first right minithoracotomy for a mitral valve replacement (MVR) followed shortly thereafter with the first robotic-assisted mitral valve procedure.

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Techniques involving a nonsternotomy or partial sternotomy incision with or without the use of CPB are included under the later section, Minimally invasive cardiac surgery.

HEARTPORT

The basic CPB requirements for robotic or minimally invasive cardiac surgery are achieved by a remote access system. One such system is the endoaortic balloon occlusion (EBO) system (Heartport, Redwood City, CA). EBO is the only established system that enables port-only endoscopic cardiac surgery, without any cardioplegia cannula in the ascending aorta. A recent long-term follow-up by Kiessling and colleagues showed no aortic degeneration or major complications over the course of 9 years. The ThruPort cannula (IntraClude, Edwards, Irvine, CA) is inserted into the common femoral artery. Then, under transthoracic echocardiography, a guide wire is advanced under transesophageal echocardiography into the ascending aorta. Then, the cannula is advanced. Venous drainage is provided by a single- or double-stage femoral venous cannula (Biomedicus 22–28 F, Edwards 24–28 F, or an ESTECH 23 or 25 F). After CPB initiation, the aortic occlusion balloon is inflated, and cardiac arrest is induced by injecting cardioplegia via the cardioplegia line. Bilateral radial artery pressure curves are used to avoid accidental occlusion of the innominate artery and to assist in monitoring balloon position. Major complications include aortic dissection, major vessel perforation, injury of intrapericardial structures, limb ischemia, myocardial infarction (MI), and neurologic events. Minor complications include minor vessel injury, groin bleeding, and lymphatic fistula. This platform allows most intracardiac procedures to be performed without sternotomy in a similar fashion to routine cardiac surgery (Fig. 1).

Minimally Invasive Direct Coronary Artery Bypass

Coronary artery bypass grafting (CABG) can be performed with CPB or without. CABG without CPB can be performed with or without open sternotomy or with minimally invasive anterior small thoracotomy; anterior small thoracotomy can include MIDCAB and minimally invasive cardiac surgery off-pump coronary artery bypass (MICS-OPCAB).

Fig. 1. (A) Endovent; (B) EndoPlege; (C) femoral venous cannula; (D) femoral arterial cannula; (E) Endoaortic balloon.
MIDCAB is also known as minimal or limited access CABG, defined as any nonsternotomy approach for CABG through a limited anterolateral thoracotomy. The LIMA is harvested through a left anterior thoracotomy or through a limited sternal split incision. The procedure can be performed with robotic assistance or without. The da Vinci system is the robotic system used and can be used for LIMA harvest. A stabilizer enables an anastomosis on the beating heart.\(^\text{10}\)

Kettering\(^\text{11}\) reported early and late mortalities of 1.3% and 3.2%, respectively. Conversion to sternotomy or CPB was 1.8%. At 6 months follow-up, 3.6% of the 445 grafts that were studied angiographically were occluded; 7.2% had significant stenosis. Better pulmonary function, quality of life, and pain management are reported in MIDCAB.\(^\text{12–14}\) Excessive rib spreading for a LIMA harvest increases the incidence of wound complications, up to 9%.\(^\text{15}\) To minimize this, thoracoscopic LIMA harvest was developed. A recent review by Dieberg and colleagues\(^\text{16}\) showed decreased intensive care unit (ICU) length of stay and cost in MIDCAB compared with conventional surgery. This procedure is most suitable for coronary arteries on the anterior surface of the heart. For isolated LAD lesions, MIDCAB is associated with decreased requirements for revascularization and major adverse coronary events compared with percutaneous coronary intervention.\(^\text{17}\)

### Minimally Invasive Multivessel Coronary Artery Bypass Grafting

Introduced by Joseph McGinn and colleagues\(^\text{18}\) in 2009, this procedure involves access to all myocardial territories via a 4- to 6-cm left fifth intercostal thoracotomy. An apical positioner and epicardial stabilizer are introduced into the chest through the subxiphoid and left seventh intercostal spaces, respectively. The left internal thoracic artery is used to graft the LAD artery, and radial artery or saphenous vein segments are used to graft the lateral and inferior myocardial territories. Proximal anastomoses are performed directly onto the aorta or from the left internal thoracic artery as a T-graft. In carefully selected patients, minimally invasive multivessel coronary artery bypass grafting (MICS CABG) has comparable mortality and outcomes to conventional CABG in the short term.\(^\text{18}\) MICS CABG was found to be cost-effective in a small study.\(^\text{19}\)

### OFF-PUMP CORONARY ARTERY BYPASS GRAFTING

In 1967, Kolessov\(^\text{20}\) first described a beating heart CABG via left anterolateral thoracotomy. Beating heart CABG via a left anterolateral thoracotomy involves performing a CABG without the use of a CPB machine. Off-pump CABG requires excellent teamwork and devices to stabilize the heart and coronary blood vessels. A recent meta-analysis by Dieberg and colleagues\(^\text{21}\) showed no difference in mortality, stroke, and MI for patients with OPCAB when compared with on-pump CABG, although the time on mechanical ventilation, time in ICU, and hospital stay were shorter in the OPCAB group compared with on-pump CABG.

### PARTIAL STERNOTOMY VALVE REPAIR AND REPLACEMENT

Partial sternotomy can be used for aortic valve replacement (AVR) and MVR. For an aortic valve replacement through a partial sternotomy (defined as any sternal incision other than median sternotomy and/or smaller than median sternotomy) inverted “T” partial upper sternotomy, “J” upper partial sternotomy, “I” sternotomy performed between the second and fifth intercostal spaces, midline lower-half sternotomy, and a “C” mini-sternotomy, leaving the upper and lower ends of the sternum intact. Right parasternal approaches have also been described, with or without resection of costal cartilages. All of these techniques promote a regular CPB and cardioplegia with a
routine AV replacement. As expected, this approach improves cosmesis, reduces the duration of mechanical ventilation and hospital stay, and decreases postoperative pain, facilitating an earlier return to normal activity. Partial sternotomy was associated with a lower cost compared with anterolateral thoracotomy and intraoperative blood loss compared with a conventional AV replacement (Fig. 2).22,23

For minimally invasive mitral valve replacement (MIMVR), a parasternal incision, inverted J-type ministernotomy over the xiphoid, upper midline sternotomy, as well as a right minithoracotomy incision have been described. Chitwood and colleagues24 proposed a classification system for minimally invasive approaches, whether the surgeon uses direct vision, thoracoscopic visualization, or robotics. Direct vision consists of surgery through a 5- to 7-cm right anterolateral minithoracotomy with or without video assistance. CPB is instituted through the femoral vessels; cardioplegia is administered, and the left ventricle is vented percutaneously. Compared with conventional MVR, MIMVR has a similar rate of reoperation, stroke, death, MV durability, shorter hospital and ICU stays, and fewer transfusions, although the incidence of complications from peripheral vascular cannulation and reexpansion pulmonary edema from a single lung ventilation are higher; furthermore, use of the parasternal approach has been abandoned because of sustained pain and chest wall instability (Fig. 3).25,26

HISTORY OF ROBOTIC CARDIAC SURGERY

Carpentier and colleagues27 did the first robotic surgery in the world by repairing an atrial septal defect (ASD) followed by an MV repair in 1998. Nifong28 did the first complete robotic MV repair in the United States in 2002. Mohr and colleagues29 in 1998 did the first robot-assisted CABG followed by Loulmet and colleagues,30 who did a totally endoscopic CABG. The first-in-human robot-assisted endoscopic AV replacement was reported by Folliquet and colleagues in 2005.31 Table 1 shows the milestones in robotic cardiac surgery.

ROBOTIC MITRAL VALVE SURGERY

Patients with asymptomatic MV disease and preserved LV function are ideal candidates for robotic MV repair. CPB is established through a femoral approach, and aortic

Fig. 2. Partial upper sternotomy.
occlusion is performed with a Chitwood cross-clamp. Five ports are inserted in the right pleural cavity to repair the MV. In specialized centers, robotic MV repair has excellent outcomes, high survival, phenomenal durability, and minimal complications regardless of disease complexity.32 Although there is a lack of proprioception or tactile feedback, robotic MV replacement enhances surgical dexterity and decreases intraoperative transfusions, hospital stay, time to return to work, and postoperative pain with outcomes comparable to that of conventional MV repair.33 Although the experience is limited with MV replacement, it can be performed with low morbidity and mortality.34 Compared with MIMVR, 30-day mortality for robotic MV repair is 2-fold lower.35 A recent systematic review showed the cost of robotic MV surgery is slightly higher than conventional surgery (Fig. 4).36

Totally Endoscopic Coronary Artery Bypass

First described by Loulmet and colleagues in 1998,30 LIMA is harvested endoscopically; a femorofemoral CPB is obtained, and the heart is arrested by occluding the ascending aorta with an endovascular balloon and infusing cardioplegic solution into the aortic root. Then, an LIMA-to-LAD anastomosis is performed using a total of 3 left-sided robotic ports. The totally endoscopic coronary artery bypass (TECAB) procedure is associated with comparable morbidity and mortality outcomes in carefully selected patients, although it is technically challenging, with longer operative times, and can be used for LAD disease only.37–41 No death, stroke, or myocardial infarction occurred in the follow-up of 41.1 months in patients with LIMA-LAD anastomosis in a recent large series; LIMA patency over the course of 3 years was 97%.42 The rate of major adverse cardiac event at 1 year was 7.0% in the TECAB group and 12.4% in the traditional CABG patients. The graft occlusion rate was also lower in the TECAB patients (1.8%) compared with 2.5% in the SYNTAX trial patients.43 Cost of TECAB is higher than conventional CABG.44
ROBOTIC ATRIAL SEPTAL DEFECT REPAIR

Robotic ASD repair has excellent outcomes.\textsuperscript{45–48} CPB is established through the femoral vessels. Five ports are used to access the right pleural cavity; aortic occlusion is performed with a Chitwood cross-clamp, and ASD is closed directly using 4-0

Table 1
Milestones in robotic cardiac surgery

<table>
<thead>
<tr>
<th>Surgery</th>
<th>Author, y</th>
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<tr>
<td>Robotic mitral valve repair</td>
<td>Carpentier et al, 1998</td>
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<td>Robotic mammary harvesting</td>
<td>Mohr, 1998</td>
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<td>Totally endoscopic coronary artery bypass with arrested heart</td>
<td>Loulmet et al, 1998</td>
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<td>Totally endoscopic coronary artery bypass off pump</td>
<td>Falk, 2000</td>
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<td>Use of BIMA in TECAB in arrested heart</td>
<td>Kappert, 2000</td>
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<td>ASD closure</td>
<td>Torraca, 2000</td>
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<tr>
<td>Totally endoscopic mitral valve repair</td>
<td>Lange, 2002</td>
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<td>LV lead implantation</td>
<td>DeRose, 2003</td>
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<tr>
<td>Use of BIMA in TECAB in beating heart</td>
<td>Farhat, 2004</td>
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<td>Aortic valve replacement</td>
<td>Folliguet, 2004</td>
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<td>Left atrial myxoma resection</td>
<td>Murphy et al, 2005</td>
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<td>Aortic valve papillary fibroelastoma resection</td>
<td>Woo, 2005</td>
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<tr>
<td>Triple vessel TECAB</td>
<td>Bonatti &amp; Srivastava, 2010</td>
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<tr>
<td>Combined mitral valve repair and CABG</td>
<td>Balkhy, 2013</td>
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Abbreviation: BIMA, bilateral internal mammary artery.

Fig. 4. The da Vinci Xi system. (©2017 Intuitive Surgical, Inc.)
Gore-Tex running suture or autologous pericardial patching, depending on the size and location of ASD. Non-CPB robotic ASD repair can be done but is associated with increased blood in the operative field and inability to perform large ASD repairs. There were no reoperations, conversion to sternotomy, or residual defect in a recent series from China (see Benjamin Wei and Robert J. Cerfolio’s article, “Robotic Lobectomy and Segmentectomy: Technical Details and Results,” in this issue). Ishikawa and colleagues reported 2-port robotic cardiac surgery for ASD using the cross-arm technique, which only used 2 ports, further improving clinical and cosmetic outcomes. Cost of robotic ASD is greater than conventional ASD closure.

**ROBOTIC MYXOMA EXCISION**

Murphy and colleagues first reported the robotic excision in 2005. The largest series reported to date showed excellent outcomes for robotic atrial myxoma excision. Compared with conventional surgery, robotic atrial myxoma excision is associated with better quality of life, pain control, earlier return to work, and decreased hospital length of stay. The authors’ group experienced similar outcomes.

**ROBOTIC SEPTAL MYECTOMY**

Endoscopic septal myectomy was first described by Casselman and Vanermen in 2002, followed by a robotic transmitral septal myectomy by Chitwood in 2012. CPB is established through the femoral vessels. A 4.5-cm minithoracotomy is made in the right fourth intercostal space followed by insertion of 4 ports; then septal myectomy is done through a transmitral approach. Septal myectomy provides excellent exposure to the interventricular septum and has good outcomes.

**SUMMARY**

Significant improvement and development have occurred in minimally invasive cardiac surgery over the past 20 years. Although most studies have consistently demonstrated equivalent or improved outcomes compared with conventional cardiac surgery, with significantly shorter recovery times, adoption continues to be limited. In addition, cost data have been inconsistent. Further ongoing trials are needed to help determine the exact roles for these innovative procedures.

**REFERENCES**


