Robotic Cardiac Surgery

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ABSTRACT: Traditionally, cardiac surgery has been performed by median sternotomy. However, a renaissance is occurring. Cardiac operations are being performed through smaller and alternative incisions with enhanced technological assistance. Both coronary artery bypass grafting and valve surgery can be accomplished with this novel methodology. Specifically, minimally invasive mitral valve surgery has become standard for many surgeons. At our institution, we have developed a robotic mitral surgery program with the da Vinci™ telemanipulation system. This system allows the surgeon to perform complex mitral valve operations through small port sites rather than a traditional median sternotomy. Our techniques and initial results are reported, as is a brief overview of the evolution of robotic cardiac surgery.

KEY WORDS: cardiac, surgery, robotic
I. INTRODUCTION

Traditional cardiac surgery is performed through a median sternotomy, which provides generous exposure and access to all cardiac structures and the great vessels. During the past decade, improvements in endoscopic technology and techniques have resulted in a substantial increase in the number of minimally invasive noncardiac surgical procedures performed. Unfortunately, because of the complexity of most cardiovascular procedures, a median sternotomy and cardiopulmonary bypass have been required.

However, in the early 1990s, alternative, less traumatic methods for performing cardiothoracic surgery were developed. The minimally invasive direct coronary artery bypass (MIDCAB) provided a single vessel bypass on the anterior surface of a beating heart through a small anterior thoracotomy. The Port-Access™ (Cardiovations Inc., Ethicon, Somerville, New Jersey) method involved endoscopic cardiac surgery on an arrested heart using novel closed-chest cardiopulmonary bypass and cardioplegic arrest methods.¹²

Nevertheless, there were many limitations that precluded the widespread adaptation of these methods. For example, standard endoscopic instruments, with only four degrees of freedom, reduce dexterity significantly. Working through fixed entry points (trocars), operators have to reverse hand motions (fulcrum effect), and at the same time, instrument drag induces the need for higher manipulation forces, leading to hand muscle fatigue.³

Computer-enhanced instrumentation systems have been developed to overcome these and other limitations. Systems can be classified according to the tasks they help perform. The first group functions as an assisting tool that holds and positions instruments. The Automated Endoscopic System for Optimal Positioning (AESOP™ 3000, Computer Motion, Inc., Santa Barbara, California) is typically used to guide an endoscope, which is controlled using voice activation. One can order the robot to hold a specific position or reorient to a specific operative field, providing a clear and steady view without tremor. The second group consists of telemanipulators that were invented to facilitate fine manipulations done under remote conditions. Connected through a controller panel, the operator’s motions direct the remote manipulator or end-effector. Currently, in cardiac surgery there are two telemanipulation systems in use—the da Vinci™ (Intuitive Surgical, Inc., Mountain View, California) and the Zeus™ robotic system (Computer Motion).

The da Vinci™ system comprises three components: a surgeon console, an instrument cart, and a visioning platform (Fig. 1). The operative console is physically removed from the patient and allows the surgeon to sit comfortably and ergonomically with his/her head positioned in a three-dimensional vision array. The surgeon’s finger and wrist movements are registered digitally, through sensors, and these
actions are transferred to an instrument cart, which operates the synchronous end-effector instruments (Fig. 2). “Wrist-like” instrument articulation emulates the surgeon’s actions at the tissue level, and dexterity becomes enhanced through combined tremor suppression and motion scaling. A clutching mechanism enables readjustment of hand position to maintain an optimal ergonomic attitude with respect to the visual field. The three-dimensional digital visioning system enables natural depth perception with high-power magnification (10×). Visualization of the internal thoracic artery, coronary arteries, and mitral apparatus is excellent.

The Zeus™ system comprises three interactive arms, mounted directly on the operating table (Fig. 3). Although the Zeus™ system lacks a fully articulated wrist and allows only four degrees of freedom, the instrument diameter is only 3.9-mm compared with the 7-mm da Vinci arm. The surgeon also works at a console that controls the instrument arms. The basic Zeus™ visualization system is two-dimensional; however, it can be used in combination with an independently developed three-dimensional visualization system.
Given the availability of telemanipulative systems, endoscopic robotic cardiac operations have become possible and have evolved through graded levels of difficulty with increasingly less exposure to a progressive reliance on video assistance. In this scheme, entry levels of technical complexity are mastered premonitory to advancing past small incision, direct-vision approaches (Level I), toward more complex video-assisted procedures (Levels II-III), and finally, to robotic cardiac operations (Level IV).

II.A. Level I: Direct Vision and Mini-Incisions

Initially, minimally invasive cardiac valve surgery was based on modifications of previously used incisions and performed under direct vision. In 1996, mini-sternotomies, parasternal incisions, and mini-thoracotomies were used in the first minimally invasive aortic valve operations.¹⁴ In Cosgrove’s first 50 aortic procedures, operative times approximated conventional operations, and mortality was 2%, with half of the patients being discharged by postoperative day five.⁵ Cohn⁴ presented his series of 41 minimally invasive aortic operations and demonstrated economic benefits. Others⁶-⁹ also found that minimal access incisions provided adequate exposure of the mitral valve. Surgical mortality (1–3%) and morbidity were comparable to those of conventional mitral surgery. Falk reported on 24 mitral valve repairs performed through a mini-incision with Port-access™ techniques.¹⁰ By 1997, the New York University group had done 27 Port-access™ mitral repairs/replacements with one death. There were no aortic dissections and no repairs had residual regurgitation requiring reoperation.¹¹

Port-access™ methods were also used for coronary artery bypass operations.¹²,¹³ Through incisions other than a median sternotomy, cardiac standstill was feasible, allowing surgeons to graft multiple vessels. Port-access™ coronary operations proved efficacious although they were more complex and required longer perfusion times. Results of a prospective multicenter trial¹⁴ on 302 consecutive patients demonstrated an operative mortality of 0.99%, with a 3.3% incidence of reoperation for bleeding and a 1.7% incidence of stroke. These encouraging results confirmed the feasibility and safety of these techniques and further advanced the next level of “minimal invasiveness.”

II.B. Level II: Video-Assisted and Micro-Incisions

Video assistance was first used for closed chest internal mammary artery harvests and congenital heart operations.¹⁵-¹⁷ Although Kaneko¹⁸ first described the use of video assistance for mitral valve surgery done through a sternotomy, it was Carpentier¹⁹ who in February 1996 performed the first video-assisted mitral valve repair via a minithoracotomy using ventricular fibrillation. Three months later, our group performed a mitral valve replacement using a microincision, videooscopic vision, percutaneous transthoracic aortic clamp, and retrograde cardioplegia.²⁰,²¹ In 1998, Mohr reported 51 minimally invasive mitral operations using
Port-access™ technology, a 4-cm incision, and three-dimensional videomicroscopy. Video technology was helpful for replacement and simple repairs; however, complex reconstructions were still approached under direct vision.²² Concurrently, our group reported 31 patients using video-assistance with a two-dimensional 5-mm camera. Complex repairs were possible and included quadrangular resections, sliding valvuloplasties, and chordal replacements with no major complications and mortality less than 1%.²³

Unfortunately, early attempts at coronary revascularization with long instruments through small incisions proved futile. Surgeons began to also use voice-activated robotic camera control to harvest internal mammary arteries with excellent facility and less patient trauma than experienced by conventional means.¹⁶ The addition of three-dimensional visualization, robotic camera control, and instrument tip articulation were the next essential steps toward a totally endoscopic procedure where wrist-like instruments and three-dimensional vision could transpose surgical manipulations from outside the chest wall to deep within the mediastinum.

II.C. Level III: Video-Directed and Port Incisions

In 1997, with the assistance of AESOP™ 3000, cardiac surgery entered the robotic age and allowed smaller incisions with better mitral valve and subvalvular visualization.²⁴ The following year, we performed the first video-directed mitral operation in the United States using the AESOP™ 3000 robotic arm and a Vista™ (Vista Cardiothoracic Systems, Westborough, Massachusetts) three-dimensional camera.²⁰,²¹ Visual accuracy was improved by voice manipulation of the camera. We now use the robotic arm, endoscope, and a conventional two-dimensional monitor routinely and have done over 300 videoscopic mitral operations successfully using this method. Recently, we reported on the use of this approach²⁵ and compared the results to a cohort who underwent conventional sternotomy. Reduced bleeding, ventilator times, and hospital stays were shown for the minimally invasive cohort.

II.D. Level IV: Video-Directed and Robotic Instruments

In 1998, Carpentier²⁶ performed the first mitral valve repair using an early prototype of the da Vinci™. Two years later,²⁷ our group performed the first complete repair of a mitral valve in North America using the da Vinci™ system. A trapezoidal resection of a large P₂ was performed with the defect closed using multiple interrupted sutures, followed by implantation of a #28 Cosgrove annuloplasty band. Subsequently, we have performed over 70 other mitral repairs as part of Food and Drug Administration (FDA)-approved trials. To date, more than 250 mitral operations have been done between Europe and North America using the da Vinci™ system. Complex mitral repairs can be done with reasonable cross clamp and perfusion times as well as excellent midterm results. Repairs have included annuloplasty band insertions, chordal replacements, sliding valvuloplasties, chordal transfers, and leaflet resections. The advancements in three-dimensional video and robotic instrumentation have progressed to a point where totally endoscopic mitral procedures are feasible. In fact, Lange and associates²⁸ performed a totally endoscopic mitral valve repair using only the 1cm ports with da Vinci™. Future refinements in these devices are needed to apply this new technology more widely.

In May of 1998, Mohr and Falk harvested the left internal mammary artery (LIMA) with the da Vinci™ system and performed the first human coronary anastomosis through a small left anterior thoracotomy incision.²⁹,³⁰ More recently, work with da Vinci™ has lead to FDA approval for internal mammary harvesting in the United States.

The first totally endoscopic coronary artery bypass (TECAB) was performed on an arrested heart at the Broussais Hospital in Paris³¹ using an early prototype of the da Vinci™ system. The Leipzig group attempted a total closed chest approach for LIMA to left anterior descending coronary artery (LAD) grafting on the arrested heart in 27 patients and were successful in twenty-two.³² Furthermore, surgeons in Europe improved the initial da Vinci™ coronary
method and eventually were able to complete bilateral internal mammary artery grafts off-pump to the anterior descending and right coronary arteries while working from one side of the chest.³³,³⁴

In September of 1998, Reichenspruner³⁵ performed an endoscopic robotically assisted coronary anastomosis using the Zeus™ system. He used a standard myocardial stabilizer inserted through a mini-thoracotomy. The pericardiotomy, vascular occlusion, and dissection of the LAD were all manually performed using conventional instruments. Damiano³⁶ first expanded coronary surgery with Zeus™ to the United States; and Boyd, at the London Health Services Center in Canada, reported on six successful closed-chest beating-heart single-vessel revascularizations using the same system.³⁷ Despite early procedural success, future refinements in these devices are needed to apply this new technology more widely.

### III. CLINICAL APPLICATIONS/PATIENT SELECTION

Early in the development of any minimally invasive cardiac surgery program, strict inclusion and exclusion criteria should be followed. In our initial experience with robotic mitral repairs, all patients had isolated mitral insufficiency. Patients with a previous right thoracotomy were excluded from the da Vinci™ procedures; however, we now approach these patients with a video-assisted mitral valve operation. Patients with severely calcified mitral annulus are not candidates. De-calcification requires further instrument development as well as a reliable means to evacuate any calcium that may fall into the left ventricle. Patients with mitral valve stenosis were excluded in the early FDA trials; however, patients treatable by commissurotomy would be suitable candidates for robotic repair. The improved visualization of the valve and subvalvular apparatus along with the maneuverability of bladed microinstruments would facilitate performance of a commissurotomy.

As previously discussed, early efforts at totally endoscopic coronary surgery using conventional instruments were discouraging and were hampered with imprecision and two-dimensional visualization. With the development of computer-assisted telemanipulation systems and three-dimensional visualization, TECAB has not only become feasible but has also been demonstrated to be safe. Nevertheless, with current technology, these operations are usually performed on single vessel (LAD) disease with either an arrested heart using the Port-Access™ system, or a beating heart using specially designed endoscopic stabilizers. Clinical trials are currently underway in Europe and North America.

### IV. OPERATIVE TECHNIQUES

#### IV.A. Mitral Valve Surgery

Pre- and postoperative surface and transesophageal echocardiographic (TEE) studies are performed. Patients are anesthetized and positioned with the right chest elevated 30°–40° and the right arm suspended, padded, and positioned over the forehead. Single left-lung ventilation is used for complete intrathoracic exposure.

Cardiopulmonary bypass is established at 26 °C using femoral arterial inflow and kinetic venous drainage through a femoral (21–23 Fr) and right internal jugular vein (17 Fr) cannula. If the femoral artery is too small or atherosclerotic, either a Bio-Medicus™ (Medtronic, Minneapolis, Minnesota, USA) or Directflow™ (Cardiovations, Somerville, New Jersey, USA) cannula can be placed through a second inter-space port for antegrade aortic perfusion. A 4–5 cm infra-mammary incision is used, and a subpectoral fourth-intercostal space (ICS) mini-thoracotomy is developed to provide cardiac access. The pericardium is opened under direct vision 2 cm anterior to the phrenic nerve. Antegrade cardioplegia is given by an aortic needle/vent placed either under direct vision or videoscopically. To minimize intracardiac air entrainment, the thoracic cavity is flooded continuously with carbon dioxide at 1–2 liters per minute. A trans-thoracic aortic cross-clamp (Scanlan International, Minneapolis, Minnesota, USA) is positioned in the
midaxillary line via a 4-mm incision in the third ICS, and intermittent antegrade cold blood cardioplegia maintains cardiac arrest and myocardial protection. Under video-assisted guidance, the posterior tine of the clamp is passed through the transverse sinus with care taken not to injure the right pulmonary artery, left atrial appendage, left main coronary, or aorta. After cardioplegic arrest, a transthoracic retractor is used to expose the mitral valve through a 3–4 cm left atriotomy made medially to the right superior pulmonary vein entrance (Fig. 4).

After valve inspection, positions for da Vinci™ left and right arm port incisions are determined. The right trocar is placed in the fourth ICS posterior lateral to the incision and parallel to the right superior pulmonary vein. Occasionally, the fifth ICS provides a better angle for the right robotic arm. The left trocar generally is placed 6 cm cephalad and medial to the right trocar, insuring internal clearance between arms to avoid both external and internal conflicts. Optimal robotic arm convergence avoids left atrial wall tearing during instrument manipulations. A high-magnification camera is used with a 30° (looking up), 3D endoscope placed through the medial portion of the mini-thoracotomy. The remainder of the incision is used as a working port for the assistant. Needles are retrieved using a long magnetic device, and suture remnants are removed from the surgical field using vacuum assistance.

Operative procedures are performed from the surgeon's console placed approximately ten feet from the operating table but in the same operating room. The patient-side assistant changes instruments and supplies and retrieves operative materials. Most often an annuloplasty band (Edwards Lifesciences, Irvine, California, USA) has been used to support repairs or provide annular reduction. In video-assisted robotic cases, early placement of annuloplasty sutures facilitates exposure during complex repairs. Exposure of each new suture often becomes predicated on retraction of the previous one. Leaflet resections, papillary muscle reconstruction, and chord insertions or transpositions should be performed after annular sutures are completed and suspended. Each suture is placed and tied intracorporeal. Upon completion of the repair, robotic devices are removed, and the left atrium is closed under direct vision to decrease operative times. Standard de-airing and weaning procedures are performed under TEE control. A typical robotic mitral valve repair is depicted in Figure 5. One month

FIGURE 4. Operative view through the working port. Note the excellent view of the mitral valve apparatus with the left atrial retractor in place seen exiting through the chest wall.

FIGURE 5. Typical da Vinci™ mitral valve repair: the P₂ segment of the posterior leaflet is being resected by robotic microscissors. The annulus is reduced and both P₁ and P₃ are approximated.
after discharge, all patients return for a follow-up visit and a transthoracic echocardiogram.

IV.B. Coronary Artery Bypass Surgery

Patients are intubated with a dual-lumen endotracheal tube, allowing single right-lung ventilation. The patient is placed on the operating room table in a supine position with the left side of the chest elevated about 30°, with the left arm placed along the body below the midaxillary line. Thoracic landmarks such as the sternal notch, xiphoid, and ribs are marked for external orientation and port placement. Proper port placement is essential for initiating endoscopic mammary artery harvesting. After deflation of the left lung, the camera port is placed bluntly in the fifth intercostal space on the anterior axillary line. The chest is insufflated with continuous CO₂ at pressures of 5–10 mm Hg to increase the available space between the heart and sternum. An endoscope is placed into this port and under visual control; two more port sites are placed, usually in the third and seventh intercostal spaces above the anterior axillary line, for both robotic arms, forming a triangle. The LIMA is mobilized from the subclavian artery all the way down to the distal bifurcation with a 30° endoscope. The distal end is skeletonized with the concomitant veins and fascia left intact to provide countertraction.

After LIMA harvesting, the patient is placed on cardiopulmonary bypass through femoral vessel cannulation if the procedure is being performed on an arrested heart. Otherwise, attention is turned to the pericardium, which is opened. The target vessel (LAD) is identified and sharply dissected free. For beating heart operations, a 1-cm skin incision is created at the subxiphoid area, and an endoscopic stabilizer is introduced. This stabilizer resembles conventional off-pump stabilizers and consists of two arms that contain special slots for attachment of silastic vessel loops used for coronary artery occlusion during the creation of the anastomosis (Fig. 6). An irrigation tube is attached to this endo-stabilizer, allowing saline flushing for clear visualization of the desired area. After placing the stabilizer onto the LAD, blood flow through this vessel is temporarily interrupted using silastic loops. After incision of the LAD with the robotic system, the anastomosis is completed on a beating heart using 7-0 polypropylene running suture. After completion of the procedure, chest tubes are placed through the camera port and the instrument port.

V. CLINICAL OUTCOMES

Currently, the world experience with robotic mitral valve surgery is mostly anecdotal, retrospective, and noncontrolled. Nevertheless, surgical results thus far have been encouraging and are hastening the way toward a completely endoscopic, robotic mitral valve operation.

FIGURE 6. Coronary stabilizer placed endoscopically as used for TECAB. Note the irrigator that provides a clear view for creation of the anastomosis.
Recently, we published our results of the first 38 mitral repairs with the da Vinci™ system.³⁸ Total robot time represents the exact time of robot deployment after valve exposure and continues until the end of annuloplasty band placement. This time decreased significantly from 1.9 hours in the first group of 19 patients to 1.5 hours in the second group. At the same time, leaflet repair times fell significantly from 1.0 hour to 0.6 hours, respectively. Also, total operating times decreased significantly from 5.1 hours to 4.4 hours in the second group of patients. Furthermore, both cross-clamp and bypass times decreased significantly with experience as well. For all patients, the total length of stay was 3.8 days, with no difference between the two groups. Of all patients in the study, 84% demonstrated a grade 3 or greater reduction in mitral regurgitation at follow-up. In the entire series there were no device-related complications or operative deaths. One valve was replaced at 19 days because of hemolysis secondary to a leak that was directed against a prosthetic chord.

In reviewing the Leipzig robotic mitral experience, Mohr described 17 patients that underwent robotic mitral valve repair.³ Fourteen of the 17 patients underwent a successful mitral valve repair with the da Vinci™ system. In three patients, conversion to conventional endoscopic instruments became necessary. The average cross clamp time was 89 ± 18 minutes. Following the repair, intraoperative TEE demonstrated no regurgitation in 13 patients and trace regurgitation in three. One patient had a grade 2 leak requiring immediate endoscopic valve replacement. Postoperative results were notable for one failure of a repair requiring emergent valve replacement on postoperative day 3 secondary to a disrupted annuloplasty ring.

To date, we have completed over 60 robotic mitral valve repairs with the da Vinci™ system and have noted certain trends. For example, bypass and cross-clamp times between the first 25 patients and the second group of 25 patients continue to significantly decrease and are currently averaging 2.69 and 2.12 hours, respectively. Suture placement time for annuloplasty rings has decreased significantly from 2.15 minutes per suture to 1.46 minutes in the second group. When P₂ robotic repair times were compared from the first group of 25 to the second, there was a significant decrease from 54.19 minutes to 30.79 minutes. A multicenter da Vinci™ trial enlisting 112 patients has recently been completed and demonstrates efficacy and safety in performing these operations by multiple surgeons at various centers, thereby becoming the first robotic telemanipulation system to become FDA approved for mitral valve repair surgery.

Similarly, experience with endoscopic coronary artery bypass surgery has been limited to only a few centers, and results are highly controlled. Because the success of coronary surgery depends on multiple, complex steps culminating in the creation of a vascular anastomosis, most clinical series have introduced robotically assisted coronary surgery in a stepwise fashion. Specifically, initial experience is limited to endoscopic LIMA harvesting, followed by a robotically assisted anastomosis through a median sternotomy, and finally a total endoscopic procedure performed on an arrested heart followed by a beating heart operation.

Currently, the largest published series of TECAB come from Europe. Wimmer-Grenecker’s group in Frankfurt reported on 45 patients that underwent TECAB on an arrested heart.³⁹ Most of these (82%) were single-vessel bypass (either LIMA–LAD or right internal mammary artery to right coronary artery). The first 22 patients had angiograms prior to discharge, revealing a 100% patency rate. Mean operative time for single-vessel TECAB was 4.2 ± 0.9 hours and 6.3 ± 1.0 hours for double-vessel bypass procedures. The average cross clamp time for single bypass was 61 ± 16 minutes and 99 ± 55 minutes for double bypass. The initial conversion rate of 22% decreased to 5% in the last 20 patients, reflecting an obvious learning curve.

Kappert⁴⁰ described TECAB in 37 patients, of which 29 were performed on a beating heart. Of these 29 patients, three received double vessel bypass using bilateral mammary arteries, and the rest were revascularized with a LIMA–LAD. As experience was
gained, the duration of surgery decreased noticeably from 280 ± 80.2 to 186 ± 58.6 minutes. An average of 30 ± 6.5 minutes for robotically performed anastomosis versus 12 ± 3 minutes for directly hand-sewn anastomoses was observed. Nevertheless, none of the 37 patients revealed any sign of delayed wound healing, but three patients did undergo a reexploration for bleeding. Currently, midterm follow-up angiography is being performed to assess graft patency.

In the United States, Damiano and colleagues\textsuperscript{41} initiated multicenter clinical trials on robotically assisted coronary surgery using the Zeus™ system. In his FDA safety and efficacy trial, 19 patients underwent a median sternotomy with cardioplegic arrest of the heart. All grafts were sewn by hand in a traditional manner except the LIMA–LAD, which was sewn robotically. Seventeen had adequate intraoperative flow (mean 38.5 ± 5 mL/min) in the LIMA graft. Anastomotic time was 22.5 ± 1.2 minutes. One patient underwent reexploration for mediastinal hemorrhage. At eight weeks’ follow-up, graft patency was assessed by angiography and all grafts were open. The average hospital stay was 4.1 ± 0.4 days.

Boyd and associates\textsuperscript{37} from London Health Sciences Center in Ontario, Canada, have also been extensively involved in initial endoscopic coronary surgery trials with the Zeus™ system. In 2000, he published a report on a series of six patients that were the first to undergo TECAB in North America on a beating heart using a specialized endoscopic stabilizer. Each of these patients had single-vessel LAD disease and underwent LIMA–LAD grafting. Special 8-0 polytetrafluoroethylene suture 7 cm in length was used to minimize suture time placement. Intracoronary shunts were used to provide needle depth landmark when performing endoscopic anastomosis with two-dimensional cameras. LIMA harvest time averaged 65.3 ± 17.6 minutes (range 50–91 min). The anastomotic time was 55.8 ± 13.5 minutes (range 40–74 min) and median operative time was 6 hours (range 4.5–7.5 h). All patients had angiographically confirmed patent grafts before leaving the hospital. The average hospital length of stay was 4.0 ± 0.9 days.

V.A. Limitations

The early clinical experience with computer-enhanced telemanipulation systems has defined many of the limitations of this approach despite rapid procedural success. The lack of force feedback is currently being addressed, and a strain sensor is being incorporated into advanced robotic surgical tools that may allow for greater control of force applied at the robotic end-effector.\textsuperscript{42} Furthermore, conventional suture and knot tying add significant time. Advancements, such as nitinol U-clips\textsuperscript{TM} (Coalescent Surgical, Sunnyvale, California, USA) should decrease operative times significantly. In a series of experiments at East Carolina University, average suture/clip placement times and knot tying/deployment times significantly decreased from 4.9 minutes to 2.6 minutes by using clips. When implanting mitral annuloplasty bands, a clip deployment time of 0.75 minutes versus 2.78 minutes for suture tying was noted.\textsuperscript{43} Because of these promising results, we have begun using the U-clip\textsuperscript{TM}. To date, four patients have had mitral annuloplasty ring implantation performed (Fig. 7) and intraoperative times have been analyzed. First, there is no difference between the placement times of the U-clip\textsuperscript{TM} and conventional suture (1.1 ± 0.5 vs. 1.5 ± 0.9 min). Most likely, this is because the motion of placing a U-clip\textsuperscript{TM} and a suture is the same. However, U-clip\textsuperscript{TM} deployment time is significantly less than suture tying time. The average deployment time of a suture is 1.1 ± 0.7 minutes versus 0.5 ± 0.2 minutes for the U-clip\textsuperscript{TM}. This novel technology may ultimately help reduce cardiopulmonary bypass time and arrested heart times in minimally invasive cardiac surgery.

For endoscopic coronary surgery, where port placements are critical to the procedure’s success, the potential use of image-guided surgical technologies will provide real-time data acquisition of physiological characteristics, allowing one to better assess the delivery of percutaneous therapy. Preoperative three-dimensional images of the thorax are acquired by both computed tomography and electrocardiogram-gated magnetic resonance imaging and are imported into a planning platform. A surgeon
may visualize and manipulate simulated objects interactively, and once optimal access port placements are determined, the positions of the simulated tools can be recorded and marked directly on the patient to specify positions for port incisions. Current research being conducted in collaboration with Carpentier is focusing on simulating and planning robotic procedures. Surgeons will have a virtual platform to analyze and plan optimal topographic surface targets that would optimize port site placement.⁴⁴⁴⁵ Such three-dimensional planning systems based on preoperative imaging data have already been introduced into other surgical specialties, including craniomaxillofacial and orthopedic surgery.⁴⁶

VI. CONCLUSION

Clearly, advances in cardiopulmonary perfusion, intracardiac visualization, instrumentation, and robotic telemanipulation have hastened a shift toward efficient and safe minimally invasive cardiac surgery. Today, cardiac surgery, particularly valve surgery done through small incisions, has become standard practice for many surgeons. Moreover, closed-chest coronary bypass surgery is in its early developmental phases.

A renaissance in cardiac surgery has begun, and robotic technology has provided benefits to cardiac surgery. With improved optics and instrumentation, incisions are smaller. The placement of wrist-like articulations at the end of the instruments moves the pivoting action to the plane of the operative field. This improves dexterity in tight spaces and allows for ambidextrous suture placement. Sutures can be placed more accurately because of tremor filtration and high-resolution video magnification. Furthermore, robotic systems may serve as educational tools. In the near future, surgical vision and training systems may be able to model most surgical procedures through immersive technology.⁴⁷⁴⁸ Thus, a “flight simulator” concept emerges where one may be able to simulate, practice, and perform the operation without a patient. Already, effective curricula for training teams in robotic surgery exist.⁴⁹

Robotic cardiac surgery is an evolutionary process, and even the greatest skeptics must concede that progress has been made. Surgical scientists must continue to evaluate this technology critically in this new era of cardiac surgery. Despite enthusiasm, caution cannot be overemphasized. Surgeons must be careful, because indices of operative safety, speed of recovery, level of discomfort, procedural cost, and long-term operative quality have yet to be defined. Traditional cardiac operations still enjoy long-term success with ever-decreasing morbidity and mortality, and thus remain our measure for comparison.

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