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REVIEW ARTICLE

Outcomes in robotic cardiac surgery

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Abstract The specialty of cardiac surgery has evolved substantially over the last 50 years, and surgical procedures that seemed impossible then are now commonly encountered in hospitals throughout the world. The latest development in this ever-evolving field is minimally invasive and robot-assisted procedures. In this article we will review the surgical outcomes reported for different series of procedures in cardiac surgery.

Keywords CABG · Cardiac surgery · Congenital surgery · Minimally invasive · Mitral valve · Robotic

Introduction

Throughout the short history of cardiac surgery, which is just over 100 years, surgeons worldwide have been determined to develop, perform, perfect, and improve cardiac operations. Our forefathers set the bar high by performing magnificent cardiac operations with excellent long-lasting results. In this ever-evolving field the goal now has become to reproduce these results using less invasive techniques, directed toward reducing complications, accelerating the recovery process, and improving patient satisfaction. Every other surgical discipline has introduced minimally invasive techniques and many of these involve totally endoscopic robotic surgery. The current end result is multidisciplinary involvement using the da Vinci robotic system to effect precise surgical tele-manipulation.

In 1998, Carpentier et al. [1] performed the first mitral valve repair utilizing an early prototype of the da Vinci system. Mohr expanded this early effort in Europe and our surgeons were fortunate to have been part of this effort. In May of 2000 our team performed the first complete robotic mitral repair with da Vinci in North America, which included a leaflet resection, reconstruction, and an annuloplasty. Since then coronary revascularizations, MAZE procedures, left ventricular lead placements, congenital heart operations, and aortic valve replacements have been performed successfully with this system and in substantial numbers. Although recent clinical data show there are benefits to robotic cardiac surgery, comparisons to conventional sternotomy operations are scarce. Surgical outcomes must be the focus of demonstration of continued progress.

Mitral valve surgery

The first Food and Drug Administration (FDA) safety and efficacy trial, was conducted at East Carolina University (ECU) in 2000, and included 20 patients [2]. Leaflet resections, sliding plasties, chordal transfers, neochord insertions, and annuloplasties were all performed successfully. This initial study revealed that although operating times were longer than for conventional mitral valve surgery, the results were very good. There were no device-related complications. The postoperative hospital stay averaged four days and all patients returned to normal activity within one month

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after surgery. Finally, early postoperative echocardiograms after 3 months revealed that none of the patients had more than trace mitral regurgitation (MR).

These initial results were encouraging and prompted a phase II multicenter FDA trial, which was completed in 2002 [3]. In this trial a total of 112 patients were enrolled at ten different institutions. Again all types of repair were performed. Nine patients (8%) had grade 2 or higher mitral regurgitation, and six patients (5%) required a reoperation. Although we regarded this initial number of reoperations as relatively high, the failures were distributed evenly among centers, with some having performed fewer than ten procedures. Most re-operations occurred in the early part of our now 300 patient series. In this initial multi-center series there were no deaths, strokes, or device-related complications, establishing the safety and efficacy for this method. These results prompted the FDA to approve the da Vinci system in November of 2002 for use in mitral valve-repair surgery.

The initial results from the first 200 ECU cases were presented at the American Heart Association Meeting in November of 2005 [4]. The average age of this patient cohort was 57 ± 0.9 years. Average operating times were: total operative = 285 min, cardiopulmonary bypass (CPB) = 156 min, and cross clamp (XC) = 119 min. Again repairs included quadrangular resections, sliding plasties, chordal transfers, chordal shortening, neochord insertion, and annuloplasties. There was one (0.5%) operative death secondary to a protamine reaction and no device or perfusion-related complications. There were also three (1.5%) hospital deaths from pulmonary and renal maladies. The hospital length of stay averaged 4.8 ± 0.2 days. Postoperative echocardiograms showed that 187 patients (93.5%) had no MR; six patients (3%) had trace MR, five patients (2.5%) had moderate MR, and two patients (1%) had systolic anterior motion of the anterior leaflet. Five patients (2.5%) required a reoperation for failed repairs, which were related either to an annuloplasty band dehiscence or progressive valvular disease. No failures were related to either a chordal insertion/transfer or leaflet dehiscence. We have repaired 60 mitral valves with bileaflet prolapse (Barlow's) without any significant residual leak.

Tatooles et al. [5] reported excellent results for 25 patients with no deaths, device-related complications, strokes, reoperations for bleeding, or incisional conversions. One patient had a transient ischemic attack seven days after surgery. Their average CPB and XC times (±SD) were 126.6 ± 25.7 and 87.7 ± 20.9 min, respectively. A total of 21 patients (84%) were extubated in the operating room, and the average length of stay was 2.7 days. For this aggressive discharge protocol, however, readmission was 28% and two patients required interval mitral valve replacements. When presented nationally there was discussion about this high rate of recidivism.

Another small series of 32 patients was reported by Jones et al. [6], who reported the safety of the procedure at a community hospital. They performed isolated mitral valve repairs and isolated mitral valve repairs combined with tricuspid valve repairs ($n = 3$). Moreover in two patients a MAZE procedure ($n = 2$) was used to treat atrial fibrillation. There were two deaths and neither was device related. Complications included three reoperations for repair failures, a stroke ($n = 1$), a groin lymphocele ($n = 1$), and a pulmonary embolism ($n = 1$).

More recently, Folliguet et al. [7] compared robotically assisted mitral valve repairs ($n = 25$) with a matched cohort undergoing a repair via sternotomy ($n = 25$). Hospitalization was statistically significant shorter for the robotic group than for the sternotomy group (7 compared with 9 days). There were no other result differences between groups. In October of 2006, Murphy and associates [8] reported their robotic mitral valve surgery experience with 127 patients. There were five conversions to median sternotomy, and one patient was converted to a mini-thoracotomy, resulting in 121 patients on whom operations were conducted robotically. Seven patients underwent a mitral replacement and 114 patients underwent repairs. Although annuloplasty bands and sutures were placed by tele-manipulation, knots were tied extracorporeally by an assistant surgeon. There was one in-hospital death, one late death, two strokes, and 22 patients developed postoperative atrial fibrillation. Transfusion of blood products was required in 37 (31%) patients. Two patients required re-operation for repair failures (1.7%). Post-discharge echocardiograms were available for 98 patients with a mean follow-up of 8.4 ± 8.1 months. A total of 87 (88.0%) patients had no MR, 8 (8.2%) patients had 1 + MR, and 3 (3.1%) patients had 2 + MR. Again, this series validates previous reports demonstrating that robotic mitral valve surgery is safe and has excellent short-term results. Studies with longer follow-up are needed, however, and surgeons must aspire to even more endoscopic mitral operations using da Vinci or another tele-manipulation system.

Atrial fibrillation surgery

There have been few case reports [9–11] of patients undergoing combined robotic mitral valve and atrial

fibrillation (MV/AF) surgery to demonstrate these procedures are safe. Only one small series of patients have undergone robotic MV/AF surgery. The results were published by Reade et al. [12] for 16 patients after combined MV/AF surgery using the Flex-10 microwave catheter (Guidant, Indianapolis, IN, USA) for left atrial ablation. The ablation added 42 ± 16 min to the MR = V repair and 1.3 days to hospitalization. At 6 months follow-up eleven patients (73%) were in sinus rhythm, three (20%) were paced, and one (7%) was in atrial fibrillation.

Coronary revascularization

The range of robot-assisted coronary operations ranges from robotic internal thoracic artery (ITA) takedowns but with a hand-sewn anastomosis, performed on or off-pump, via either a median sternotomy or a mini-thoracotomy, to the ''so-called'' totally endoscopic coronary artery bypass (TECAB) procedure. Early reports demonstrated the feasibility and safety of harvesting the ITA with the da Vinci system. Acceptable learning curves and harvest times of <30 min were achieved after the technique was mastered [13–15].

There have been many early case reports and small series of robot-assisted coronary operations. Not until recently did larger series from experienced centers emerge, however. Subramanian et al. [16] reported 30 patients undergoing robot-assisted multi-vessel off-pump CABG via a mini thoracotomy. The average number of grafts was 2.6. There were no mortalities (30-day follow-up) and 29 patients (97%) were extubated in the operating room. Two patients required re-exploration for bleeding, and one patient required a sternotomy for further grafting. Half of the patients were discharged within 24 h and only two patients stayed in the hospital more than 3 days.

Using a similar surgical technique, Turner and Sloan [17] reported 70 patients with no operative mortality. The average operating time was 4 h, however, and there was a clear learning curve (operating times 5 h and 56 min for the first ten cases and 3 h and 52 min for the last ten cases). Complications included re-exploration for bleeding (n = 2, 2.8%), atrial fibrillation (n = 6, 8.5%), and infections (n = 2, 2.8%). All were extubated within 24 h of surgery and the average length of stay was 5.7 days. The largest single institution series was that of Srivastava et al. [18], with 150 patients undergoing robotic assisted bilateral IMA harvest and off-pump CABG via mini thoracotomy. The average number of arterial grafts was 2.6 ± 0.8 per patient. There were no mortalities, myocardial infarctions, strokes, or wound infections. Re-exploration for bleeding was required for four patients, however. The mean postoperative length of stay was 3.6 ± 2.9 days.

In the prospective multi-center TECAB Argenziano et al. [19] described 98 patients requiring single-vessel ITA-LAD grafting who were enrolled at 12 centers. Thirteen patients (13%) were excluded intraoperatively because of inability to perform the operation. Mean CPB and arrest times for the other 85 patients was 117 ± 44 and 71 ± 26 min, respectively, with length of stay averaging 5.1 ± 3.4 days. Although there were no deaths or strokes, there was one early reintervention, one myocardial infarction, and five (6%) conversions to the open technique. Short-term arteriographic follow-up at 3 months (n = 76) revealed significant stenosis (>50%) or occlusion in six patients. Although overall freedom from re-intervention was 91%, conversions and anastomotic complications rendered the results somewhat disappointing. Despite sporadic failures in early series of both on and off-pump robot-assisted CABG operations, use of the method is increasing. Perhaps multi-vessel small thoracotomy bypass grafting, facilitated by robotic graft harvesting, will be the answer. Combination of percutaneous revascularization and LAD robotic grafting remains attractive for use in selected patients. Irrespective of the method, long-term follow-up is still necessary to determine if these techniques are comparable with the excellent results achieved by use of median sternotomy.

Left ventricular lead placement

Numerous prospective studies have demonstrated that biventricular (BiV) pacing improves ventricular function, exercise capacity, and quality of life in patients with congestive heart failure and delayed interventricular conduction. A recent meta-analysis also revealed survival improved after BiV pacing**.** Although leads are most often placed by use of transvenous techniques, 15 to 25% of transvenous implantations fail. At this point surgical intervention is required. Early reports by DeRose et al. [20] attested to the efficacy of robot-assisted left ventricular lead implantation. They reported results for thirteen patients, six (46%) of whom had a previous CABG, with no complications or technical failures. Navia's series, combining minimally invasive (via mini thoracotomy) and robotic/endoscopic LV lead placements, included 41 patients without mortality, intraoperative complications, or implantation failures [21]. This approach is very attractive and could become the preferred technique, because sur-

geons should be able to determine the best epicardial site for implantation by mapped stimulation. This could result in markedly increased lead placement success and improved ventricular function compared with current transvenous techniques. A randomized study comparing both techniques is in progress.

Congenital surgery

A few congenital cardiac conditions are amenable to minimally invasive or robotic repairs. del Nido and Suematsu [22] summarized their early robotic congenital cardiac surgery results. A robot was used at the Boston Children's Hospital mainly for management of extracardiac lesions, including the patent ductus arteriosus (PDA) and vascular rings [23]. Their average age for PDA closures ($n = 15$) or vascular ring repairs ($n = 6$) was 8.3 ± 4.7 years. Total operating times were somewhat long at 170 ± 46 min (PDA) and 167 ± 48 min (vascular ring). There were no complications and only one conversion to a thoracotomy. All patients were extubated in the operating room with a mean postoperative hospital stay of 1.5 days.

Again robotic surgery for intra-cardiac lesions has been limited. Morgan et al. [24] reported eleven patients undergoing robotic atrial septal defect (ASD) repairs and five having closure of a patent foramen ovale. They demonstrated improved quality of life in eight variables after robotic procedures compared with patients having either a sternotomy or mini thoracotomy. There were no group differences between time to return to work or length of hospitalization, however.

Summary

Although robotic cardiac surgery is still evolving, early results from experienced centers are encouraging and are comparable with those from traditional cardiac surgical techniques. Demonstrated advantages include fewer blood transfusions, reduced hospitalization, faster return to normal daily activity, and improved quality of life. As technology continues to improve, these procedures will continue to become more common among cardiac centers. Evolution of adjunctive devices and techniques will also improve access to, and workspace in, confined intra-cardiac operations. To determine if robotic techniques could become the new standard in cardiac surgery, long-term results are imperative.

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