

## State-of-the-art - Cardiac general Robot-assisted cardiac surgery

Paul Modi, Evelio Rodriguez, W. Randolph Chitwood Jr.\*

East Carolina Heart Institute, East Carolina University, Pitt County Memorial Hospital, 600 Moye Boulevard, Greenville, NC 27834, USA

Received 10 February 2009; received in revised form 5 June 2009; accepted 7 June 2009

### Summary

Recognition of the significant advantages of minimizing surgical trauma has resulted in a substantial increase in the number of minimally invasive (MI) cardiac surgical procedures being performed. Synchronously, technological advances in optics, instrumentation and perfusion technology have facilitated routine totally endoscopic robotic cardiac surgery using the da Vinci<sup>®</sup> telemanipulation system (Intuitive Surgical Inc). This technology has been applied to many cardiac surgical procedures, in particular, mitral valve repair (MVP) and totally endoscopic coronary artery bypass grafting (TECAB), allowing the surgeon to operate through 5 mm port sites rather than a traditional median sternotomy. In this rapidly evolving field, we review the clinical results of robotic cardiac surgery.

© 2009 Published by European Association for Cardio-Thoracic Surgery. All rights reserved.

**Keywords:** Surgical procedures; Minimally invasive; Thoracic surgery; Video-assisted; Robotics; Telemedicine/instrumentation

### 1. Introduction

During the past decade, recognition of the significant advantages of minimizing surgical trauma by reducing incision size and eliminating rib-spreading have resulted in a substantial increase in the number of minimally invasive (MI) cardiac surgical procedures being performed. These benefits have included less pain, shorter hospital stays, faster return to normal activities and improved cosmesis [1]. At the same time, improvements in surgical instrumentation, perfusion technology and visioning platforms have facilitated these advances such that MI approaches have now become the standard of care at certain institutions worldwide due to excellent results. Endoscopic instrumentation, with only four degrees of freedom, significantly reduces the dexterity needed for delicate cardiac surgical procedures, and the loss of depth perception by using two-dimensional video monitors further increases operative difficulty. Robotic surgery provides a solution to these problems and represents a paradigm shift in the delivery of healthcare for both the patient and the surgeon.

Robotic systems consist of telemanipulators where end-effectors, or micro-instruments, are controlled remotely from a console. The da Vinci<sup>®</sup> S system (Intuitive Surgical, Mountain View, CA, USA) is the most widely used and is comprised of a surgeon console, an instrument cart and a visioning platform. The operative console allows the surgeon to immerse himself into the operative field through high-definition three-dimensional imaging. Finger and wrist movements are registered through sensors and translated into motion-scaled tremor-free movements avoiding the

fulcrum effect and instrument shaft shear forces common to long-shafted endoscopic instruments. Wrist-like articulations at the ends of micro-instruments bring the pivoting action of the instrument to the plane of the operative field improving dexterity in tight spaces and allowing truly ambidextrous suture placement.

The greatest growth in robotic procedures has been in the field of urology with rapid dissemination of robot-assisted radical prostatectomy worldwide. Currently, over 1700 robotic cardiac operations are performed in the USA per year but with a yearly increase of about 400 cases, or about 25% growth per year [2]. The most common applications in cardiac surgery are for mitral valve repair (MVP) and endoscopic coronary artery bypass grafting (CABG). The last 15 months have, however, seen two critical editorials in the Journal of Thoracic and Cardiovascular Surgery questioning the clinical value of robotics in cardiac surgery [2, 3]. This article will review the published evidence, assess the limitations of robotic technology and look at likely future directions.

### 2. Mitral valve repair

The first robotic MVP was performed in May 1998 by Carpentier using an early prototype of the da Vinci<sup>®</sup> articulated intracardiac 'wrist' robotic device [4]. A week later, Mohr performed the first coronary anastomosis and repaired five mitral valves (MVs) with the device [5]. Grossi et al. of New York University partially repaired a MV using the Zeus<sup>™</sup> system (Computer Motion Inc, Goleta, CA, USA) but no annuloplasty ring was inserted. Four days later, in May 2000, Chitwood performed the first complete da Vinci<sup>®</sup> mitral repair in North America. Two Food and Drug Administration (FDA) trials subsequently led to approval in Novem-

\*Corresponding author. Tel.: +1 252 744 4822; fax: +1 252 744 3051.  
E-mail address: chitwoodw@ecu.edu (W.R. Chitwood Jr.).

ber 2002 of the da Vinci® system for MV surgery [6, 7]. Although a small (3–4 cm) utility incision is still necessary for the patient-side surgeon to pass sutures and needles in and out of the chest, advances in 3D visualization and instrumentation, particularly the development of the robotic left atrial EndoWrist® retractor, have progressed to a point where totally endoscopic mitral procedures using the full spectrum of Carpentier's repair techniques are routinely practiced.

There are no randomized studies comparing robotic to either video-assisted or sternotomy MV surgery. However, in a non-randomized study, Woo et al. demonstrated that robotic surgery patients had a significant reduction in blood transfusion and length of stay compared to sternotomy patients [8], whereas the only difference that Folliguet et al. noted was a shorter hospital stay (7 days vs. 9 days,  $P=0.05$ ) [9]. The largest reported single center experience is 300 cases with 0.7% and 2.0% 30-day and late mortalities, respectively [10]. No sternotomy conversions or MV replacements were required. Immediate post-repair echocardiograms showed 98% had either no or trivial residual mitral regurgitation (MR). Complications included 2 (0.7%) strokes, 2 (0.7%) transient ischemic attacks, 3 (1.0%) myocardial infarctions and 7 (2.3%) re-operations for bleeding. The mean hospital stay was  $5.2 \pm 4.2$  (S.D.) days and 16 (5.3%) patients required a re-operation at a mean of  $319 \pm 327$  days from the original operation. Mean postoperative echocardiographic follow-up at  $815 \pm 459$  (S.D.) days demonstrated that 7.6% had moderate or severe recurrent MR. Five-year Kaplan–Meier survival was equivalent to conventional surgery at  $96.6 \pm 1.5\%$  with  $93.8 \pm 1.6\%$  freedom from re-operation.

Murphy et al. reported their experience in 127 patients of which five were converted to median sternotomy [11]. Seven patients underwent mitral valve replacement (MVR) and 114 had MVPs. Complications included one in-hospital and one late mortality as well as a 1.6% incidence of stroke and 17% new onset of atrial fibrillation (AF). Post-discharge echocardiogram results were available in 98 patients with a mean follow-up of 8.4 months. There was no more than 1+ residual MR in 96.2%. These two series demonstrate that robotic MV surgery is safe with excellent short-term results and is associated with good mid-term durability. As more experience has been gained with the use of robotic techniques, surgeons are tackling more complex MV disease such as anterior and bileaflet repairs with results comparable to published national data using conventional techniques [12]. Nevertheless, long-term follow-up is needed to determine whether these results will be comparable to the 10- and 20-year data reported by others. As technology continues to improve, these procedures will become easier and more reproducible and better results will likely follow. Comparative data on pain, speed of recovery, quality of life and return to work are necessary to assess the benefits that have been demonstrated for other MI and robotic cardiac procedures [13].

### 3. Coronary revascularization

The range of robotic coronary operations ranges from internal mammary artery (IMA) harvest with a hand-sewn

anastomosis, performed either on- or off-pump through a mini-thoracotomy or median sternotomy, to totally endoscopic coronary artery bypass grafting (TECAB). Anastomoses in all coronary territories have been successfully performed even in sequential configuration and using anastomotic couplers [14]. Early reports demonstrated the feasibility and safety of harvesting the IMA with the da Vinci® system with harvest times <30 min achievable once the learning curve had been negotiated [15].

In 1998, Loulmet demonstrated the feasibility of TECAB on an arrested heart by using da Vinci® to harvest the left IMA (LIMA) and to perform a LIMA to left anterior descending (LAD) coronary anastomosis in two patients [16]. In 2000, Falk reported TECAB on 22 patients of which four were converted to mini-thoracotomy for anastomotic bleeding or graft issues [17]. In the remaining 18 patients, grafts were widely patent at three months with no major complications. The same group subsequently reported the first off-pump TECAB using an endoscopic stabilizing device [18]. Dogan reported 45 arrested heart TECAB procedures in 2002, of which eight patients underwent double-vessel revascularization with both IMAs [19]. The initial conversion rate of 22% dropped to 5% in the last 20 patients, a trend which is mirrored in other studies [20]. The procedural time for single-vessel TECAB was  $4.2 \pm 0.4$  h, cardiopulmonary bypass (CPB) time was  $136 \pm 11$  min and aortic cross-clamp (XC) time was  $61 \pm 5$  min.

Subramanian achieved multi-vessel revascularization (mean number of grafts, 2.6) in 30 patients using robotically-harvested IMAs [21]. Depending on the specific target, either a mini-thoracotomy or transabdominal approach was employed. Twenty-nine (97%) patients were extubated on the operating table, 77% were discharged within 48 h and only two patients needed readmission. In addition, only one patient needed conversion to sternotomy and there was no mortality. However, the largest single institution series comes from Srivastava with 150 patients undergoing robotic-assisted bilateral IMA harvesting and off-pump CABG via a mini-thoracotomy [22]. Two patients presented with chest pain after discharge secondary to graft occlusion; in both cases, treatment using percutaneous intervention was successful. In 55 patients undergoing computed tomography angiography at 3 months, all 136 grafts were patent.

A multicenter Investigational Device Exemption trial was reported by Argenziano in 2006 [23]. Ninety-eight patients requiring single-vessel LAD revascularization were enrolled at 12 centers; 13 patients (13%) were excluded intraoperatively (e.g. failed femoral cannulation, inadequate working space). In the remaining 85 patients who underwent TECAB, CPB time was  $117 \pm 44$  min, XC time was  $71 \pm 26$  min and hospital length of stay was  $5.1 \pm 3.4$  days. There were 5 (6%) conversions to open techniques. There were no deaths or strokes, one early reintervention and one myocardial infarction. Three-month angiography was performed in 76 patients, revealing significant anastomotic stenoses (>50%) or occlusions in six patients (7.1%). Overall freedom from reintervention or angiographic failure was 91% at three months. US FDA approval of use of da Vinci® for coronary revascularization was largely based on this study.

The largest multicenter experience was reported by de Cannière et al. in 2007 and involved five European institu-

tions with 228 patients undergoing TECAB (on-pump,  $n=117$ ; off-pump,  $n=111$ ) [20]. The overall mortality was 2.1% and the conversion rate of 28% decreased with time and did not adversely affect outcome. The overall procedural efficacy, as defined by angiographic patency or lack of ischemic signs on stress electrocardiography, was 97% at six months. The incidence of major adverse cardiac events within six months was 5%. The rate of target vessel reintervention was slightly higher for both on- and off-pump procedures compared to that reported for open procedures in the Society of Thoracic Surgeons national database.

In summary, these reports of robotically-assisted coronary surgery have mostly involved highly-selected patient populations requiring limited revascularization usually of the anterior wall. In these circumstances, surgeons have been able to achieve totally endoscopic LIMA-LAD grafting with high success rates albeit after the initial learning curve. It is still not clear whether TECAB or robotically-enhanced MI direct CABG provides superior outcomes. Hybrid or integrated revascularization effectively combines the survival benefits of LIMA-LAD grafting as a MI procedure with PCI of a second or third coronary target. Integrating these two procedures into one therapeutic modality aims to provide the patient with the beneficial aspects of each successive technique in the least invasive way possible. It is likely to become utilized more frequently particularly with advances in robotic instrumentation. Recent work by Katz has demonstrated that this approach can be accomplished with no mortality, low peri-operative morbidity and excellent 3-month angiographic LIMA patency (96.3%) [24]. Kiaii et al. recently reported 91% LIMA-LAD patency at 9 months for simultaneous integrated coronary revascularization using a robotically-enhanced technique [25]. Five-year freedom from reintervention of the LAD after robotic TECAB is 87.2% which leaves room for improvement but is reflective of the early experience typically associated with new techniques [26]. Refinements in anastomotic technology, endoscopic stabilization and target vessel identification systems will all facilitate routine TECAB.

#### 4. AF surgery

The Cox-Maze III procedure is an effective surgical treatment for AF. However, it is not widely applied due to its complexity, increased operative times, and the risk of bleeding. Various energy sources have been introduced to simplify the traditional 'cut and sew' approach and also to allow the development of less invasive therapies. There have been a few case reports of patients undergoing combined robotic MV and AF (MV/AF) surgery demonstrating that these procedures are safe [27-29]. One small ( $n=16$ ) series of patients undergoing robotic MV/AF surgery using the Flex-10 microwave catheter (Guidant, Indianapolis, IN) from our own institution has been reported [30]. The ablative procedure added  $42 \pm 16$  min to the MV repair and 1.3 days to hospitalization. At six months follow-up, 73% were in sinus rhythm, 20% were paced and 7% were in AF. In our overall robotic experience, about 18% of patients undergoing MV surgery have a concomitant procedure for AF, usually a cryomaze [10].

Robotically-assisted surgery for lone AF is in its infancy being first reported in an animal model in 2002 [31] and later in humans in 2004 [28, 32, 33] to achieve pulmonary vein isolation. An on-pump endocardial approach has been reported by ourselves and others [34] using cryoablation to replicate the Cox-Maze III lesion set and further results are awaited.

#### 5. Left ventricular lead placement

Numerous prospective studies have demonstrated that cardiac resynchronization therapy with or without implantable cardioverter-defibrillator capability improves ventricular function, exercise capacity and quality of life, as well as reducing mortality and heart failure hospitalizations in patients with symptomatic heart failure and delayed intraventricular conduction despite optimal medical therapy [35]. Left ventricular lead placement is usually accomplished percutaneously through coronary sinus cannulation, advancing the lead into a major cardiac vein. This technique is associated with long fluoroscopy times and is not applicable to all patients because of anatomical limitations in coronary venous anatomy. Early and late failures occur in ~12% and 10% of procedures, respectively [36]. Surgical epicardial lead placement is often a rescue therapy for these patients.

Early reports by Derosé et al. demonstrated the efficacy of robot-assisted LV lead implantation [37]. They reported results for 13 patients, six of whom had previous CABG, with no complications or technical failures. Navia's series of mini-thoracotomy or robotic/endoscopic LV lead placement included 41 patients without mortality, intra-operative complications or implantation failures [38]. A MI surgical approach is very attractive as it allows surgeons to determine the best epicardial site for implantation by mapped stimulation and may, therefore, entail greater success rates than transvenous implantation. A randomized study comparing both techniques is in progress.

#### 6. Intra-cardiac tumor resection

Cardiac tumors, although relatively uncommon and mostly benign, should almost always be resected to prevent thromboembolic complications. Murphy et al. recently reported robotic excision of three left atrial myxomas using either a left atriotomy or right atriotomy with trans-septal approach. Autologous pericardial patches were used to repair septal defects following excision [39]. The mean CPB and XC times were  $103 \pm 40$  min and  $64 \pm 2$  min, respectively. Impressive results were reported with all patients being discharged on day 4 and resuming normal activity three weeks after surgery. Similarly, Woo et al. used robotic techniques to excise an aortic valve papillary fibroelastoma with the patient being discharged on the 3rd postoperative day and back to work within one month [40].

#### 7. Congenital surgery

A few congenital cardiac conditions in both children and adults lend themselves to a MI approach. Torracca et al. and Wimmer-Greinecker et al. were the first to report small series of patients undergoing robotic atrial septal

defect (ASD) repair in Europe [41, 42]. In a US FDA Investigational Device Exemption trial, Argenziano et al. demonstrated that ASDs in adults can be closed safely and effectively using totally endoscopic robotic approaches with a median XC time of 32 min [43]. One of 17 patients had a residual shunt across the atrial septum which was repaired via mini-thoracotomy on postoperative day 5. The reoperative finding was that the atrial septal primary suture line was intact but there was a tear medial to it. This failure was therefore likely related to use of a direct closure technique rather than using a patch repair and therefore not a failure of the robotic technique per se. Bonaros et al. showed that the learning curve is steep and associated with a rapid decrease in operative times [44]. Morgan subsequently demonstrated that robotic ASD closure hastens postoperative recovery and improves quality of life compared to either a mini-thoracotomy or median sternotomy approach [13].

Del Nido's group from the Boston Children's Hospital published their 2-year experience with 15 patients undergoing patent ductus arteriosus (PDA) closure ( $n=9$ ) or vascular ring repair ( $n=6$ ) utilizing the da Vinci<sup>®</sup> system [45]. The patients were aged 3–18 years and only one was converted to a thoracotomy because of pleural adhesions. The total operative times were a little prolonged at  $170 \pm 46$  min (PDA) and  $167 \pm 48$  min (vascular ring). Nevertheless, all were extubated in the operating room and were discharged after a median of 1.5 days. Le Bret et al. compared operative times for robotically-assisted PDA closure using the Zeus System (Computer Motion, Inc, Goleta, CA) vs. videothoracoscopic surgery and noted similar operative times to Del Nido's group (162 min) for the robotic cohort but much shorter durations for the videothoracoscopic cohort (83.5 min), with equivalent clinical outcomes [46].

## 8. Limitations

Limitations specifically related to the use of robotic techniques in cardiac surgery include:

1. *Incomplete and delayed motion tracking* – while tele-manipulation systems may eventually enhance endoscopic surgical performance by eliminating some human deficits such as tremor, such systems not only add a second information processing system but also cause inertia by additional electronic and mechanical parts. This was elegantly demonstrated by Jacobs et al. in 20 subjects using an endoscopic trainer designed to simulate beating-heart conditions [47]. The subjects were asked to touch targets manually or robotically with the da Vinci<sup>®</sup> system with different patterns of increasing index of difficulty (resting model and moving at frequencies of 35, 60 and 90 bpm). Robotic assistance slowed task completion by 2.9 times and increased the error rate. At a frequency of 90 bpm, robotic tracking became much more difficult. However, these data must be interpreted in the context that the subjects had no prior robotic experience and, as we have seen, there is a clear learning curve. These limitations might negatively affect dexterity and the quality of an anastomosis in beating-heart surgery. Therefore, future progress must

be directed to ensuring better quality stabilization, development of algorithms for virtual immobilization, increased bandwidth and different hardware design that will allow for a faster response.

2. *Lack of tactile feedback* – in our experience, visual clues such as tissue deformation provide adequate information. Reiley et al. demonstrated that visual force feedback primarily benefits novice robot-assisted surgeons with diminishing benefits among experienced surgeons [48].
3. *Cost* – initial capital outlay, instruments and maintenance. These will come down with time and may be justified by a reduction in hospital stay, patient morbidity, invasiveness and speed of recovery. Morgan et al. specifically addressed this issue and found an increase in hospital costs of \$3444 for robotic MVP compared to a sternotomy approach when factoring in the initial capital investment of the system [49].
4. *Learning curve* due to the inherent complexity of the system. Training programs are conducted in formal training centers and consist of didactics, familiarization with the system and then practice on inanimate objects, cadavers and live animals [50].
5. *Additional operative time* to position the robotic system and for instrument changes.

## 9. Conclusion

Robotic cardiac surgery is an evolutionary process and we are simply at one point on a continuum. If 'time were told' on robotic cardiac surgery as Dr Robicsek's editorial in the February 2008 issue of the Journal of Thoracic and Cardiovascular Surgery would have us believe, then why is there a 25% yearly increase in the number of robotic operations being performed in the US? Statistics he presents such as '65% of US cardiac surgical institutions that own a da Vinci<sup>®</sup> do not use it' are not surprising when the uptake of robotic technology has grown to 25% of all US cardiac surgical programs. Clearly many centers have hopped on the 'robotic bandwagon' only to be disappointed. It is unlikely that this growth in robotic technology is being mirrored in Europe. This expensive technology is now becoming concentrated in a few reference centers where the cost of robotic technology can be offset against a high institutional volume and where the necessary surgical expertise and experience exist. This is also necessary from a research and development perspective if we are to overcome some of the current limitations of this approach.

Although the surgical robot allows unprecedented closed chest surgical access to the heart, it is only one of many new tools that are prerequisite for successful MI cardiac surgery. Further development of new adjunctive technologies such as retraction and stabilization systems, sutureless anastomotic devices and image guidance systems is vital. Miniaturization of technology will enable us to progress to routine totally endoscopic cardiac surgery through incisions of only a few millimeters in diameter. This will require a combined effort of physicians with our industry partners to fill in the technological gaps that are present in our current armamentarium of MI tools.

It is vital to ensure success that formal training in these MI and robotic techniques is obtained. It is likely that in the future surgical vision and training systems will be able to model most surgical procedures through immersive technology, much like a 'flight simulator', where one may be able to simulate, practice and perform the operation without a patient. Surgical scientists must continue to critically evaluate this technology. Despite enthusiasm, caution cannot be overemphasized as traditional cardiac operations still enjoy proven long-term success and ever-decreasing morbidity and mortality and remain our measure for comparison.

## References

- [1] Modi P, Hassan A, Chitwood WR Jr. Minimally invasive mitral valve surgery: a systematic review and meta-analysis. *Eur J Cardiothorac Surg* 2008;34:943–952.
- [2] Robicsek F. Robotic cardiac surgery: time told! *J Thorac Cardiovasc Surg* 2008;135:243–246.
- [3] Damiano RJ Jr. Robotics in cardiac surgery: the Emperor's new clothes. *J Thorac Cardiovasc Surg* 2007;134:559–561.
- [4] Carpentier A, Loulmet D, Aupecle B, Kieffer JP, Tournay D, Guibourt P, Fiemeyer A, Meleard D, Richomme P, Cardon C. [Computer assisted open heart surgery. First case operated on with success]. *CR Acad Sci III* 1998;321:437–442.
- [5] Mohr FW, Falk V, Diegeler A, Autschbach R. Computer-enhanced coronary artery bypass surgery. *J Thorac Cardiovasc Surg* 1999;117:1212–1214.
- [6] Nifong LW, Chu VF, Bailey BM, Maziarz DM, Sorrell VL, Holbert D, Chitwood WR Jr. Robotic mitral valve repair: experience with the da Vinci system. *Ann Thorac Surg* 2003;75:438–442; discussion 43.
- [7] Nifong LW, Chitwood WR, Pappas PS, Smith CR, Argenziano M, Starnes VA, Shah PM. Robotic mitral valve surgery: a United States multicenter trial. *J Thorac Cardiovasc Surg* 2005;129:1395–1404.
- [8] Woo YJ, Nacke EA. Robotic minimally invasive mitral valve reconstruction yields less blood product transfusion and shorter length of stay. *Surgery* 2006;140:263–267.
- [9] Folliguet T, Vanhuysse F, Constantino X, Realli M, Laborde F. Mitral valve repair robotic versus sternotomy. *Eur J Cardiothorac Surg* 2006;29:362–366.
- [10] Chitwood WR, Rodriguez E, Chu MWA, Hassan A, Ferguson TB, Vos PW, Nifong LW. Robotic mitral valve repairs in 300 patients: a single center experience. *J Thorac Cardiovasc Surg* 2008;136:436–441.
- [11] Murphy DA, Miller JS, Langford DA, Snyder AB. Endoscopic robotic mitral valve surgery. *J Thorac Cardiovasc Surg* 2006;132:776–781.
- [12] Rodriguez E, Nifong LW, Chu MWA, Wood W, Vos PW, Chitwood WR. Robotic mitral valve repair for anterior leaflet and bileaflet prolapse. *Ann Thorac Surg* 2008;85:438–444.
- [13] Morgan JA, Peacock JC, Kohmoto T, Garrido MJ, Schanzer BM, Kherani AR, Vigilance DW, Cheema FH, Kaplan S, Smith CR, Oz MC, Argenziano M. Robotic techniques improve quality of life in patients undergoing atrial septal defect repair. *Ann Thorac Surg* 2004;77:1328–1333.
- [14] Dogan S, Aybek T, Westphal K, Mierdl S, Moritz A, Wimmer-Greinecker G. Computer-enhanced totally endoscopic sequential arterial coronary artery bypass. *Ann Thorac Surg* 2001;72:610–611.
- [15] Vassiliades TA Jr. Technical aids to performing thoracoscopic robotically-assisted internal mammary artery harvesting. *Heart Surg Forum* 2002;5:119–124.
- [16] Loulmet D, Carpentier A, d'Attellis N, Berrebi A, Cardon C, Ponzio O, Aupecle B, Relland JY. Endoscopic coronary artery bypass grafting with the aid of robotic assisted instruments. *J Thorac Cardiovasc Surg* 1999;118:4–10.
- [17] Falk V, Diegeler A, Walther T, Banusch J, Brucierus J, Raumans J, Autschbach R, Mohr FW. Total endoscopic computer enhanced coronary artery bypass grafting. *Eur J Cardiothorac Surg* 2000;17:38–45.
- [18] Falk V, Diegeler A, Walther T, Jacobs S, Raumans J, Mohr FW. Total endoscopic off-pump coronary artery bypass grafting. *Heart Surg Forum* 2000;3:29–31.
- [19] Dogan S, Aybek T, Andressen E, Byhahn C, Mierdl S, Westphal K, Matheis G, Moritz A, Wimmer-Greinecker G. Totally endoscopic coronary artery bypass grafting on cardiopulmonary bypass with robotically enhanced telemanipulation: report of forty-five cases. *J Thorac Cardiovasc Surg* 2002;123:1125–1131.
- [20] de Canniere D, Wimmer-Greinecker G, Cichon R, Gulielmos V, Van Praet F, Seshadri-Kreaden U, Falk V. Feasibility, safety, and efficacy of totally endoscopic coronary artery bypass grafting: multicenter European experience. *J Thorac Cardiovasc Surg* 2007;134:710–716.
- [21] Subramanian VA, Patel NU, Patel NC, Loulmet DF. Robotic assisted multivessel minimally invasive direct coronary artery bypass with port-access stabilization and cardiac positioning: paving the way for outpatient coronary surgery? *Ann Thorac Surg* 2005;79:1590–1596; discussion 1596.
- [22] Srivastava S, Gadasalli S, Agusala M, Kolluru R, Naidu J, Shroff M, Barrera R, Quismundo S, Srivastava V. Use of bilateral internal thoracic arteries in CABG through lateral thoracotomy with robotic assistance in 150 patients. *Ann Thorac Surg* 2006;81:800–806; discussion 806.
- [23] Argenziano M, Katz M, Bonatti J, Srivastava S, Murphy D, Poirier R, Loulmet D, Siwek L, Kreaden U, Ligon D. Results of the prospective multicenter trial of robotically assisted totally endoscopic coronary artery bypass grafting. *Ann Thorac Surg* 2006;81:1666–1674; discussion 1674–1675.
- [24] Katz MR, Van Praet F, de Canniere D, Murphy D, Siwek L, Seshadri-Kreaden U, Friedrich G, Bonatti J. Integrated coronary revascularization: percutaneous coronary intervention plus robotic totally endoscopic coronary artery bypass. *Circulation* 2006;114(1 Suppl):I473–I476.
- [25] Kiaii B, McClure RS, Stewart P, Rayman R, Swinamer SA, Suematsu Y, Fox S, Higgins J, Albion C, Kostuk WJ, Almond D, Sridhar K, Teefy P, Jablonsky G, Diamantouros P, Dobkowski WB, Jones P, Bainbridge D, Iglesias I, Murkin J, Cheng D, Novick RJ. Simultaneous integrated coronary artery revascularization with long-term angiographic follow-up. *J Thorac Cardiovasc Surg* 2008;136:702–708.
- [26] Kappert U, Tugtekin SM, Cichon R, Braun M, Matschke K. Robotic totally endoscopic coronary artery bypass: a word of caution implicated by a five-year follow-up. *J Thorac Cardiovasc Surg* 2008;135:857–862.
- [27] Bolotin G, Kypson AP, Nifong LW, Chitwood WR Jr. Robotically-assisted left atrial fibrillation ablation and mitral valve repair through a right mini-thoracotomy. *Ann Thorac Surg* 2004;78:e63–e64.
- [28] Loulmet DF, Patel NC, Patel NU, Frumkin WI, Santoni-Rugiu F, Langan MN, Subramanian VA. First robotic endoscopic epicardial isolation of the pulmonary veins with microwave energy in a patient in chronic atrial fibrillation. *Ann Thorac Surg* 2004;78:e24–e25.
- [29] Akpınar B, Guden M, Sagbas E, Sanisoglu I, Caynak B, Bayramoglu Z. Robotic-enhanced totally endoscopic mitral valve repair and ablative therapy. *Ann Thorac Surg* 2006;81:1095–1098.
- [30] Reade CC, Johnson JO, Bolotin G, Freund WL Jr, Jenkins NL, Bower CE, Masroor S, Kypson AP, Nifong LW, Chitwood WR Jr. Combining robotic mitral valve repair and microwave atrial fibrillation ablation: techniques and initial results. *Ann Thorac Surg* 2005;79:480–484.
- [31] Argenziano M, Garrido MJ, Williams MR, Nifong LW, Smith CR, Oz MC. A totally endoscopic, beating-heart approach to pulmonary vein isolation for the treatment of atrial fibrillation. *Heart Surg Forum* 2002;5(Suppl II):S191.
- [32] Gerosa G, Bianco R, Buja G, di Marco F. Totally endoscopic robotically-guided pulmonary veins ablation: an alternative method for the treatment of atrial fibrillation. *Eur J Cardiothorac Surg* 2004;26:450–452.
- [33] Jansens JL, Ducart A, Preumont N, Jottrand M, Stefanidis C, Stoupele E, de Canniere D. Pulmonary vein isolation by robotic-enhanced thoracoscopy for symptomatic paroxysmal atrial fibrillation. *Heart Surg Forum* 2004;7:E595–E598.
- [34] Cheema FH, Weisberg JS, Khalid I, Roberts HG Jr. Warm beating heart, robotic endoscopic Cox-cryomaze: an approach for treating atrial fibrillation. *Ann Thorac Surg* 2009;87:966–968.
- [35] McAlister FA, Ezekowitz J, Hooton N, Vandermeer B, Spooner C, Dryden DM, Page RL, Hlatky MA, Rowe BH. Cardiac resynchronization therapy for patients with left ventricular systolic dysfunction: a systematic review. *J Am Med Assoc* 2007;297:2502–2514.
- [36] Alonso C, Leclercq C, d'Allonnes FR, Pavin D, Victor F, Mabo P, Daubert JC. Six-year experience of transvenous left ventricular lead implantation for permanent biventricular pacing in patients with advanced heart failure: technical aspects. *Heart* 2001;86:405–410.

- [37] Derose JJ Jr, Belsley S, Swistel DG, Shaw R, Ashton RC Jr. Robotically assisted left ventricular epicardial lead implantation for biventricular pacing: the posterior approach. *Ann Thorac Surg* 2004;77:1472–1474.
- [38] Navia JL, Atik FA, Grimm RA, Garcia M, Vega PR, Myhre U, Starling RC, Wilkoff BL, Martin D, Houghtaling PL, Blackstone EH, Cosgrove DM. Minimally invasive left ventricular epicardial lead placement: surgical techniques for heart failure resynchronization therapy. *Ann Thorac Surg* 2005;79:1536–1544; discussion 44.
- [39] Murphy DA, Miller JS, Langford DA. Robot-assisted endoscopic excision of left atrial myxomas. *J Thorac Cardiovasc Surg* 2005;130:596–597.
- [40] Woo YJ, Grand TJ, Weiss SJ. Robotic resection of an aortic valve papillary fibroelastoma. *Ann Thorac Surg* 2005;80:1100–1102.
- [41] Torracca L, Ismeno G, Alfieri O. Totally endoscopic computer-enhanced atrial septal defect closure in six patients. *Ann Thorac Surg* 2001;72:1354–1357.
- [42] Wimmer-Greinecker G, Dogan S, Aybek T, Khan MF, Mierdl S, Byhahn C, Moritz A. Totally endoscopic atrial septal repair in adults with computer-enhanced telemanipulation. *J Thorac Cardiovasc Surg* 2003;126:465–468.
- [43] Argenziano M, Oz MC, Kohmoto T, Morgan J, Dimitui J, Mongero L, Beck J, Smith CR. Totally endoscopic atrial septal defect repair with robotic assistance. *Circulation* 2003;108(Suppl 1):II191–II194.
- [44] Bonaros N, Schachner T, Oehlinger A, Ruetzler E, Kolbitsch C, Dichtl W, Mueller S, Laufer G, Bonatti J. Robotically assisted totally endoscopic atrial septal defect repair: insights from operative times, learning curves, and clinical outcome. *Ann Thorac Surg* 2006;82:687–693.
- [45] Suematsu Y, Mora BN, Mihaljevic T, del Nido PJ. Totally endoscopic robotic-assisted repair of patent ductus arteriosus and vascular ring in children. *Ann Thorac Surg* 2005;80:2309–2313.
- [46] Le Bret E, Papadatos S, Folliguet T, Carbognani D, Petrie J, Aggoun Y, Batisse A, Bachet J, Laborde F. Interruption of patent ductus arteriosus in children: robotically assisted versus videothoracoscopic surgery. *J Thorac Cardiovasc Surg* 2002;123:973–976.
- [47] Jacobs S, Holzhey D, Kiaii BB, Onnasch JF, Walther T, Mohr FW, Falk V. Limitations for manual and telemanipulator-assisted motion tracking – implications for endoscopic beating-heart surgery. *Ann Thorac Surg* 2003;76:2029–2035; discussion 2035–2036.
- [48] Reiley CE, Akinbiyi T, Burschka D, Chang DC, Okamura AM, Yuh DD. Effects of visual force feedback on robot-assisted surgical task performance. *J Thorac Cardiovasc Surg* 2008;135:196–202.
- [49] Morgan JA, Thornton BA, Peacock JC, Hollingsworth KW, Smith CR, Oz MC, Argenziano M. Does robotic technology make minimally invasive cardiac surgery too expensive? A hospital cost analysis of robotic and conventional techniques. *J Cardiac Surg* 2005;20:246–251.
- [50] Kypson AP, Nifong LW, Chitwood WR Jr. Robot-assisted surgery: training and re-training surgeons. *Int J Med Robot* 2004;1:70–76.