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Review Article

Robotic Cardiac Surgery: A Systematic Review of the Past and Present

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Abstract

Development and evolution has accompanied the human race since the very beginning-technical, economic or social. Curiosity of the human mind and need of the hour has led to consistent discoveries and inventions. Medical sector has perennially faced the challenges of expansion and ability to provide new and better ways of diagnosis and treatment, reducing risk and cost and enhancing overall benefits. Robotic surgery is the beginning of one such revolution in surgical sphere, considered a paradigm shift by many. This innovative technology has been implemented in the field of cardiac surgery and its use has proliferated over the last 15 years. The anesthesiology team also requires coping up with the new challenges.

Keywords: Robotic surgery, Minimally invasive cardiac surgery, Da vinci surgical system™, Cardiac surgery, TEE, One lung ventilation, Capnothorax

Introduction

In 1921 Czech playwright Karel Capek introduced the term and the concept of Robot in his play *Rossom's Universal Robots* to indicate forced labor [1,2] (Czech Robota-Forced labor). Later the concept was modified by Isaac Asimov in different science fiction stories and novels popularly known as "The Robot Series". Technology has evolved the robots over years from some dumb machines to automatically controlled, reprogrammable, multipurpose manipulator which not only able to follow the commands but also an artificial human replica which can perform jobs which are impossible by even the most trained human hands. The application of robotics has been extended to various aspects of science and technology but the introduction of robotics in medical science has brought about a revolution and ushered a new era in medical development. In the last few decades the penetration of robotics in the field of surgery has revolutionized the concept of minimally invasive surgery and currently being considered a paradigm shift in the history of surgery.

The practice of cardiac surgery revolved around open heart surgery concept, where median sternotomy was used to open the chest and cannulation of great vessels including aorta and venae cavae was done to ensure adequate perfusion in on pump procedures.

In last few decades this concept has been changed to minimally invasive cardiac surgery which incorporated small incisions, avoidance of median sternotomy if possible, use of femorofemoral bypass in selected cases leading to less perioperative trauma, fast postoperative recovery and better cosmetic outcome [3]. The minimally invasive cardiac surgery is itself a challenge to the cardiac surgeons for less visualization of operative field, less exposure, poor access to the structures and difficult dissection. This type of surgery requires significant surgical skill and mastery over the procedure.

Beginning from their inception, the surgical robots have been aimed to extend the human capabilities beyond the limits of physical boundaries. Initial applications of robots including PUMA 560 for brain biopsy or PROBOT for prostate surgery opened up a new horizon to minimally invasive and endoscopic surgeries. First application of robots in cardiac surgery goes back to 1998 when Carpentier successfully used an earlier prototype of da Vinci surgical system™ for mitral valve repair [4]. Followed by this Mohr repaired five mitral valves and performed a coronary revascularization with the device [5]. First robotic mitral valve repair in north America was reported by Chitwood in 2000 [6]. Currently the practice of robotic surgery has extended beyond the developed countries and it is not impossible that robotic hand will replace the human hands in all type of surgical procedures in near future (Table 1).

Year	Name	Place	Developed by	Used for
1983	Arthrobot [7]	Vancouver	Dr. James McEwen, Geof Auchinleck, Dr. Brian Day	Orthopedic procedures. Assisted by a scrub nurse robot and a medical laboratory robotic arm.
1985	Puma 200, Puma 560	Danbury, Connecticut, USA	Unimation	Brain biopsy
1992	Robodoc	Sacramento, CA	Integrated Surgical Supplies Ltd + IBM	Hip replacement
1988	Probot	London	Imperial college, London	Prostate surgery

2000	Artemis	Eberhard Karls University	Schurr MO, Buess G, Neisius B, Voges U.	Endoscopic surgery
1997	AESOP	Santa Barbara, CA	Computer Motion, Inc.	Endoscopic surgery Automated Endoscopic System for Optimal Positioning
1995	da Vinci surgical system™		SRI International and Intuitive Surgical + DARPA + NASA	Urological surgeries General laparoscopic surgeries General non-cardiovascular thoracosopic surgeries Thoracoscopically-assisted cardiotomy procedures
2001	Zeus		SRI International and Intuitive Surgical + DARPA + NASA	
12 May, 2008	Neuroarm		University of Calgary and Foothills Medical Centre in Calgary, Alberta, Canada	Image guided robot compatible neurosurgery
June 2008	Mirosurge		the German Aerospace Centre	Minimally invasive surgery
Sept 2010	Sofie		Eindhoven University of Technology	Force feedback assisted surgical robot

Table 1: History of surgical robots

USFDA Approved Robot for Cardiac Surgery-da Vinci Surgical System™

Da Vinci surgical system™ was approved for cardiac surgery in 2002. It is a comprehensive master slave surgical robot and incorporates the tele-manipulation technology developed by NASA and US Army. The key components of da Vinci surgical system™ include a surgeon console, a patient side cart, interactive robotic arms, a 3D HD visual system and Endowrist™ instruments. The surgeon console is physically remote from the patient where the surgeon sits comfortably while viewing a 3D HD vision of the operative field. Below the display there is master control which senses the movements of the surgeons' hand, wrist and finger and efficiently transfers the scaled and filtered movements to the instrument cart. The patient is positioned in the patient side cart during surgery and three to four robotic arms are used to carry out the surgeon's command. The movement of the surgeon is transmitted through the Endowrist™ instruments which have seven degrees of freedom and equipped with quick release levers which speed instrument change during surgery.

Advantages and Disadvantages of Robotic Cardiac Surgery

The advantages of robotic cardiac surgery are essentially both due to minimally invasive technique and improvement in endoscopy. Currently the most common techniques employ a 3-4 cm mini thoracotomy or a 2cm lateral working port [8]. The robotic arms have better accuracy, improved hand eye coordination, and better visualization due to better 3D imaging. The robots offer improved dexterity by virtue of increase degree of freedom, distal articulation, tremor filter and avoidance of fulcrum effect. This improved dexterity helps in placement of a scope to locations with minimal tissue handling which was previously considered as impossible. The prime disadvantage of this technique is cost. For a robotic surgery set-up not only the robotic instruments are costly, the whole set-up has to be refreshed in a new form and the persons associated needs to be trained which involves a large amount of money which is difficult to afford. Among technical disadvantages the lack of human sensation creates difficulty in assessment of structures (Tables 2 and 3).

Advantage of minimally invasive technique	Mechanical advantage	Other advantages
Avoidance of sternotomy Very small incision Less surgical trauma Reduced bleeding Less blood product utilization Lower infection risk Less pain Shorter hospitalization Faster recovery Better cosmesis Greater patient satisfaction [9]	Six degrees of freedom Tremor-free movements Ambidexterity Avoidance of fulcrum effect	Better visualization through the use of three-dimensional high-definition imaging [8]. Remote surgery is possible

Table 2: Advantages of robotic and robotic assisted minimally invasive surgery

Robotic Cardiac Surgeries

The most commonly performed robotic cardiac surgery worldwide is mitral valve repair. Robotic assisted coronary revascularization also gained popularity and being increasingly used (Table 4).

Disadvantage	
Absence of touch sensation [10]	Steep learning curve [12]
Very expensive	Incomplete and delayed motion tracking [13]
High start-up cost [11]	Increased operative time
May require extra staff to operate	
Large instruments.	
Unproven benefit	

Table 3: Disadvantage of robotic and robotic assisted minimally invasive surgery

Commonly performed	Less commonly performed
Mitral valve repair	LV lead placement
Coronary revascularization/ Totally Endoscopic Coronary Artery Bypass Grafting (TECAB)	PDA closure
Cox-Maze III for AF	
Intra-cardiac tumor excision	
ASD repair	

Table 4: Scope of robotic cardiac surgery

Mitral Valve Repair

Mitral valve repair or replacement is the most commonly performed robotic assisted cardiac surgery worldwide. The first robotic mitral repair was performed by Carpentier in 1996 [14] and the first mitral valve replacement was done by Chitwood later the same year [15]. Mihaljevic et al. [16] compared 261 patients undergoing robotic mitral valve repair to 114 patients via complete sternotomy, 270 patients via partial sternotomy and 114 patients via right mini anterolateral thoracotomy and found more cardiopulmonary bypass time but fewer incidences of atrial fibrillation, pleural effusion and hospital stay in the robotic surgery group. Woo and co-workers [17] in a non-randomized study found robotic surgery is associated with significant reduction in blood transfusion and length of stay compared to sternotomy patients. Chitwood WR Jr and associates [18] reported a large single-centre experience on robotic mitral valve surgery between 2000 and 2006 of 300 patients who had undergone robotic mitral valve repair with da Vinci Surgical System™. They used 3- to 4-cm right intercostal access, transthoracic aortic occlusion, and peripheral cardiopulmonary bypass for their procedure. No sternotomy conversions or mitral valve replacements were required. They found 30 days mortality of 0.7% and 2% late mortality. Complication included stroke (0.7%), transient ischemic attack (0.7%), myocardial infarction (1%) and reoperation for bleeding (2.3%). Their observation revealed safety and good midterm durability of robot assisted mitral valve surgery. Murphy and co-workers [19] conducted a retrospective review of 127 patients undergoing endoscopic robotic mitral valve surgery from 2002 to 2005. They used 4 right chest ports with femoral perfusion and endoaortic balloon occlusion. In hospital mortality was 0.8% and late mortality was the same. Reoperation rate was 1.6%. They opined in favor of robotic mitral valve repair in selected patients. In 2005, Nifong and associates [20] reported results of a United States multicentric trial of robotic mitral valve repair. They used peripheral cardiopulmonary bypass, a 4- to 5-cm right minithoracotomy, a transthoracic aortic cross clamp, and ante grade cardioplegia. There was no deaths, stroke or device related complications. Leaflet repair times averaged 36.7 +/- 0.2 minutes, with annuloplasty times of 39.6 +/- 0.1 minutes. Total robot, aortic cross clamp, and cardiopulmonary bypass times were 77.9 +/- 0.3 minutes, 2.1 +/- 0.1 hours, and 2.8 +/- 0.1 hours, respectively. Reoperation rate was 5.4%.

These studies indicate robotic mitral valve surgery is safe and associated with good midterm durability in selected patients. With advancement in robotic design and associated technology more complex procedures will be conducted through this minimally invasive technique.

Coronary Revascularization and TECAB

The range of robotic coronary revascularization ranges from internal mammary artery (IMA) harvest, a hand-sewn anastomosis between IMA and left anterior descending artery performed either on- or off-pump through a mini-thoracotomy or median sternotomy, to totally endoscopic coronary artery bypass grafting (TECAB). Anastomosis in all coronary artery territory has been described in literature even with sequential grafts [21].

The robotic surgery involves a significant learning curve for the surgeon. In a practiced hand left internal thoracic artery (LITA) harvest usually takes 30-40 minutes and in some institutions this technique is routinely performed [22,23]. A brief description of LITA harvest technique is described in Figures 1 and 2.

- One lung ventilation achieved with double lumen Endobronchial tube or bronchial blocker.
- Patient's right side is elevated to 30^0
- Cardiopulmonary bypass is achieved either by femoral artery and vein cannulation or by bi-caval venous cannulation (right internal jugular and femoral veins) and femoral arterial cannulation. In patients with either inadequate femoral artery size or aorto-iliac atherosclerotic disease, the right axillary artery is cannulated.
- Chitwood transthoracic aortic cross-clamp.
- Antegrade crystalloid Bretschneider's cold cardioplegia
- Hypo-thermic (26⁰C) fibrillatory arrest
- Robotic instrument arm trocars are inserted into the chest, and the da Vinci™ surgical cart is docked by the patient's left side.
- Repair technique:
  1. limited triangular or quadrangular resection,
  2. folding valvuloplasty,
  3. chordal shortening either by trans-location or papillary muscle folding,
  4. neochord implantation,
  5. leaflet sliding-plasty

Figure 1: Brief description of MVR procedure [8].

1. Patient supine ,left chest slightly elevated and left arm lowered
2. One lung ventilation with CO2 insufflation upto 10 mm hg.
3. A 30^0 scope angled up introduced in 4^{th} intercostal space
4. Instrument port in 3^{rd} and 6^{th} intercostal space
5. Ports may be in triangular fashion with central camera port a little lower or in almost linear fashion.
6. ITA is dissected using low energy diathermy as a pedicle from first rib to sixth intercostal space in a skeletonised fashion.
7. To avoid torsion, pedicle is not detached from the chest wall until completion of anastomosis
8. For bilateral ITA harvest, the right pleural space is opened and right ITA is dissected using a 0^0 scope

Figure 2: Brief description of robotic assisted internal thoracic artery harvest

The first described TECAB procedure was reported by Loulmet and coworkers [24] in 1999. Since then multiple centers worldwide has employed this technique successfully. Falk V and co-workers [25] reported 22 cases of TECAB performed through four ports with elective conversion to minthoracotomy in four patients. Operating times were in the range 220-507 min. Median intubation time was 13 hour and stay on ICU and hospitalization was 20 hour and 7 days, respectively. A 3-month follow-up angiography revealed patent grafts in all TECAB patients. Mohr FW and associates [26] reported successful takedown of ITA in 79 of 81 patients and successful completion of TECAB in 22 out of 27 cases. At 3 months follow up angiography showed 95.4% patency of grafts in the TECAB group. Wang S, Zhou J and Cal JF [27] performed a meta-analysis of 16 studies and found compared with traditional CABG, TECAB or robot-assisted coronary artery bypass (RACAB) had lower rates of major adverse cardiac or cerebrovascular events (MACCE) 12 months postprocedure (7.0% vs. 12.4%; odds ratio [OR], 0.53; confidence interval [CI], 0.38-0.74; $p<0.05$). Subgroup analysis highlighted the differences between TECAB and RACAB as follows: TECAB decreased the rate of renal failure requiring hemofiltration (OR, 0.25; CI, 0.07-0.88), wound infection (OR, 0.11; CI, 0.11-1.99), and stroke (OR, 0.14; CI, 0.02-0.77) during follow-up, but increased the need for re-exploration for bleeding and MACCE (OR, 2.18; CI, 1.14-4.16; $p<0.05$).

Atrial Fibrillation Ablation

The improved dexterity and excellent visualisation offered by da Vinci surgical system^{TM} has been successfully exploited for precise placement of probes for atrial fibrillation ablation. Nifong et al. [20] reported a series of 86 patients undergoing combined robotic mitral valve repair with cryomaze and the result was excellent. Pruits and co-workers have reported 33 paroxysmal and 17 permanent atrial fibrillation patients treated by thoracoscopic or robot assisted off pump epicardial microwave ablation and the results were excellent [28,29].

Key Elements to Establish a Robotic Surgery Set-Up

Success of robotic surgery does not only depend on the skill of the operator surgeon but also reflects composite skill and training of the entire surgical team. This also includes experienced cardiac anesthesiologist, perfusionists, nurses and operating room staffs as well as the other equipment's used in this procedure. Trans esophageal echocardiography plays a crucial role in this procedure to predict safe cannulation, plan complex valve repair, and monitor cardiac filling and emptying and to diagnose complications at the earliest. Attending cardiac anesthesiologist must be skilled in trans esophageal echocardiography because access to the patient and visualization may be limited during the surgery. Different patient positioning and surgical technique may bring about another array of hemodynamic complexity and attending cardiac anesthesiologist must be prepared for this. Monitoring may be difficult and different options should be considered prior to final positioning. The nursing staffs and other operating room personnel must be conversant with the technique because the robotic surgery set up is completely different. Skill, training and sincerity form the backbone of a successful robotic surgery team. And finally back up preparation and referral facility is essential to prevent catastrophe.

Conclusion

The advancement in science has always been coursed through a rough path. The beginners had to pay great price and the evolution of technology always came at a cost of sacrifice. Maybe one day the robotics will be the only answer to the surgical problems of the heart. But today what the pessimists may see is some very expensive large instruments in the hand of some personnel at different stages of the learning curve and with no proved significantly improved mortality. Does the cost really meet the benefit? Is the machine better than the man? May be the answer is hidden somewhere in the future.

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