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Abstract

To date, more and more cardiac surgeons are moving toward smaller incisions and the use of specialized less invasive surgical methodologies. The use of (and advances in) less invasive approaches or minimally invasive cardiac surgery can minimize or eliminate complications that may occur in conventional cardiac surgery. For example, for some surgeons, partial sternotomy and minithoracotomy have supplanted standard sternotomy as their preferred route for aortic valve and mitral surgeries.

Keywords

Less invasive cardiac surgery • Cardiac robotic surgery • Minimally invasive cardiac surgery • Incision size • Laparoscopic surgery • Thoracoscope • Minithoracotomy • Partial sternotomy • Partial thoracotomy • Off-pump beating heart coronary artery bypass grafting surgery

35.1 Introduction

The history of cardiac surgery reflects a constant search by cardiac surgeons for safer and less invasive ways to treat their patients. Since Dr. F. John Lewis' pioneering operation in 1952, followed by Dr. C. Walton Lillehei's first successful series of intracardiac defect repairs in the mid-1950s, cardiac surgery as a surgical subspecialty has expanded dramatically. Notably, one of the most important technological innovations in cardiac surgery was the development and modification of a cardiopulmonary bypass machine. For years, this machine has been used extensively by cardiac surgeons. Its use has enabled cardiac surgery to become a safe and reproducible daily routine in many hospitals across the world. Nowadays, though most cardiac operations are con-

sidered somewhat standardized, the continued pursuit of less invasive surgical approaches, as well as recognition of the importance of quick postoperative recovery and quality of life, remains significant for patients and physicians.

In recent years, there have been continued efforts to provide and adapt "less invasive cardiac surgery" as standard care. All four of the major steps used in conventional cardiac surgery need to be considered when attempting to develop less invasive modifications: (1) gaining access to the heart through a full sternotomy; (2) supporting the vital organs through a cardiopulmonary bypass machine; (3) arresting the heart by administering cardioplegia; and/or (4) manipulating the ascending aorta during aortic cannulation, during cross-clamping and side-clamping, and during proximal anastomosis in coronary artery bypass grafting. Unfortunately, any of these steps can impose significant risks or adverse effects. More specifically, a large incision typically corresponds to greater pain, a more noticeable scar, more complications, and/or a longer recovery time. Similarly, cardiopulmonary bypass has been known to trigger adverse inflammatory reactions and/or subsequently cause multiple organ dysfunction. Finally, manipulating the aorta can lead to strokes

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(e.g., plaque dislodgement) and/or other neurologic deficits. Importantly, less invasive approaches or minimally invasive cardiac surgery can minimize or eliminate complications that may occur relative to each of the four steps commonly used in conventional cardiac surgery. This chapter focuses on less invasive methodologies commonly employed in adult cardiac surgical procedures.

35.2 Impact of Incision Size

For years, the physical and emotional impact of a large incision size on the individual patient has been ignored by most cardiac surgeons. Historically, adequate exposure of the target tissue or organ through large skin incisions took priority over concern about incision size; this mind-set remained unchallenged until the early 1990s. Subsequently, with novel specially designed instruments, experience with laparoscopic surgery demonstrated that those surgical procedures traditionally performed through large incisions could actually be accomplished with much smaller incisions. More recently, the patient benefits of small incisions have been clearly shown including less pain, quicker recovery, lower infection rate, shorter hospital stays, and/or better quality of life [1, 2]. In some studies, less immune function disturbance has also been reported [3]. Encouraged by positive results from the laparoscopic surgical community, cardiac surgeons began to modify their approaches to perform less invasive cardiac surgery. Currently, a variety of approaches have been used to replace full sternotomy: (1) thoracoscopy or minithoracotomy and/or (2) partial sternotomy. Nevertheless, cardiopulmonary bypass support, if required, is established through cannulation in the peripheral vessels such as the femoral arteries, femoral veins, and internal jugular veins. Various studies have reported advantages with smaller incisions or sternum-sparing incisions in terms of pain, blood loss, postoperative respiratory function, time to recovery, infection, cosmesis, and survival rate [4–7]. However, one must also consider that smaller incisions have certain drawbacks. In order to have the same access and visualization as with larger incisions, special instruments and specialized surgical skills are required, and only selected patients are eligible. For surgeons, the initial learning curve to be able to perform such procedures clinically can be very steep. Nevertheless, smaller incisions are certainly very appealing to both patients and referring physicians. To date, more and more surgeons are moving toward smaller incisions and the use of these specialized less invasive surgical methodologies. For some surgeons partial sternotomy and minithoracotomy have supplanted standard sternotomy as their preferred route for aortic and mitral valve surgeries.

35.3 Side Effects of Cardiopulmonary Bypass

Cardiopulmonary bypass procedures have become commonplace in cardiac surgical suites; however, capabilities to perform the same clinical procedure safely without its use would be desirable, for such bypass procedures are not performed without risk. More specifically, cardiopulmonary bypass has been associated with a complex systemic inflammatory reaction in the host patient. The hallmarks of this reaction are typically increased microvascular permeability in multiple organs, resulting in an increase in interstitial fluid and the activation of humoral amplification systems. The complement system, including the kallikrein-bradykinin cascade, the coagulation cascade, the fibrinolytic cascade, and the arachidonic acid cascade, is activated. Inflammatory mediators, such as cytokines and proteolytic enzymes, are released.

In most classic cardiac cases where cardiopulmonary bypass is utilized, the heart is stopped to provide for a motionless field. Cardiac arrest is initiated with infusion of cardioplegia to the myocardium. Unfortunately, subsequent reperfusion of the heart can cause ischemic reperfusion injury to the myocardium.

Clinical manifestations of this systemic inflammatory reaction and myocardial ischemic reperfusion injury can be subtle but also serious and even lethal in some patients. The incidence of this systemic reaction has been reported in 5–30 % of cardiac surgery patients after cardiopulmonary bypass [8–13]. Importantly, this inflammatory response can affect multiple organs. More specifically, examples of this systemic response can vary: (1) from transient subtle cognitive impairment to a permanent stroke, (2) from coagulopathy requiring transfusion of blood products to disseminated intravascular coagulation, (3) from pulmonary edema to adult respiratory distress syndrome requiring prolonged ventilation support, (4) from low cardiac output to acute heart failure requiring inotropic or mechanical circulatory support, and/or (5) from transient kidney insult with increased creatinine to permanent kidney failure requiring hemodialysis. Any of these, or a combination thereof, commonly result in prolonged intensive care unit stays requiring intense monitoring and often increased patient mortality. Importantly, the severity of these reactions tends to be related to cardiopulmonary bypass time, the patient's age, and/or comorbidities [11, 12].

To date, coronary artery disease remains as the leading cause of death for individuals living in developed countries. Despite widespread use of drug-eluting stents in treating coronary artery disease and sharply decreased patient volume for coronary artery bypass grafting (CABG) numbers,

CABG operations still remain the most commonly performed cardiac procedures in the United States. Compared to percutaneous coronary artery interventions such as stenting, CABG has shown advantages of improved patient event-free survival and lower re-intervention rate, especially in patients with multivessel coronary artery disease, diabetes, and decreased left ventricular function. These benefits are attributed mainly to the use of in situ left internal mammary artery bypass to the left anterior descending artery, in which the patency rate remains over 90 % even after 15 years of implantation. Furthermore the use of bilateral internal mammary arteries as bypass conduits has shown to offer a better patient survival rate and less reoperation rate, when compared with the use of only left internal mammary artery as a bypass conduit.

In the past 15 years, off-pump beating heart coronary artery bypass grafting surgery (OPCABG, a less invasive surgical approach) has entered the mainstream of clinical cardiac surgical practice, and the number of such procedures has been steady in the United States, making up ~10–20 % of all CABG surgeries performed annually. An increasing number of studies, including prospective randomized studies, have demonstrated that when compared to conventional CABG, OPCABG procedures result in: (1) a lower incidence of postoperative neurologic deficits, (2) fewer blood transfusions, (3) shorter intubation times, (4) less release of cardiac enzyme, (5) less renal insult, (6) shorter ICU stays, (7) less release of cytokines IL 8 and IL 10, and/or (8) lower mortality [13–17]. It should be noted that the difference in these parameters between OPCABG and CABG procedures mostly ranges from 2 to 10 %. In most OPCABG procedures, however, there has been the tendency to bypass fewer vessels; this may result in an incomplete revascularization. Moreover, certain anatomic locations and the nature of target coronary arteries may preclude safe and reliable anastomoses with OPCABG, e.g., arteries located in the posterolateral wall of hypertrophied hearts, intramyocardial arteries, and severely calcified arteries. Furthermore, with today's available methodologies, OPCABG is more challenging technically for most cardiac surgeons. It should also be noted that emergency conversion of OPCABG to conventional CABG because of hemodynamic instability carries a significantly higher morbidity and mortality rate than conventional CABG (about 6 times higher mortality) [18]; fortunately, the overall conversion is rare, with a rate of only 3.7 %.

Though OPCABG surgery took off rapidly in the earlier part of the last decade, the enthusiasm for OPCABG has faded in recent years due to the lack of highly anticipated “drastic” clinical benefits of this procedure over conventional CABG and the additional technical challenges faced by the surgeons. Currently OPCABG comprises 10–20 % of all CABG procedures performed in the United States, which has decreased compared to 10 years ago. Although isolated

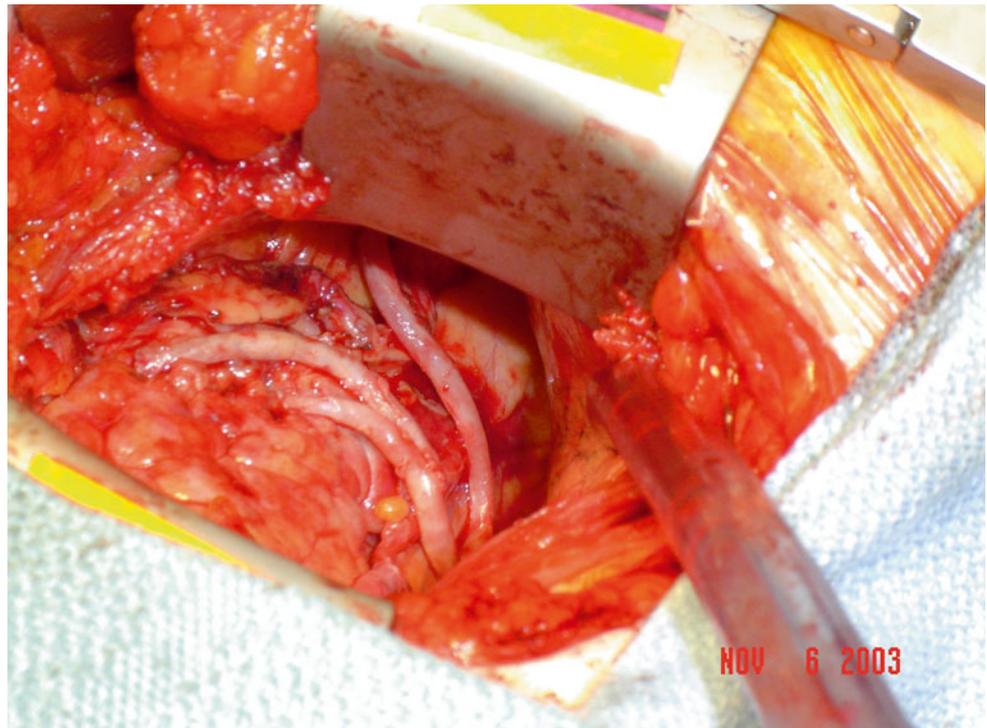
centers perform virtually all CABG procedures off-pump, in many centers, OPCABG is a seldom-used procedure. Such a large discrepancy appears due to the lack of effective education of practicing surgeons and a steep learning curve to master the tricks of performing OPCABG.

35.4 Effects of Manipulating the Aorta

Coronary artery disease is often considered as a component of systemic vascular disease. The same risk factors that contribute to coronary artery disease, such as smoking, diabetes, hypertension, and hyperlipidemia, also contribute to carotid artery disease and atherosclerotic changes in the aorta; this is especially true for the ascending aorta. Atheroma in the aorta can present with calcified plaques or with “cheese-like” soft plaques, which can be disrupted (dislodged) during: (1) cannulation of the ascending aorta for cardiopulmonary bypass, (2) cross-clamping in general, and/or (3) side-clamping of ascending aorta for attachment of proximal anastomoses of bypassed grafts. The mobilized plaques can then cause microembolization or macroembolization of brain vessels, resulting in neurologic deficits. Multiple episodes of microembolic events have been documented by transcranial Doppler studies during routine CABG surgery. The number of microembolic signals is reported to be related to the extent that the ascending aorta is manipulated [19]. Nevertheless, calcified areas of the aorta (or porcelain aorta) can be identified by palpation and thus avoided during surgery, whereas soft plaques are typically unnoticed until they are disrupted during surgical manipulation. The incidence of plaque formation in the ascending aorta can be as high as 30 % [20].

Recently, several methodologies have been described to avoid disrupting plaques when working in the region of the ascending aorta. For example, topical ultrasound devices have been used to identify hidden plaques, especially the soft types. In addition, a single aortic cross-clamp technique has been shown to reduce the risk of plaque disruption during conventional CABG surgery [21]. Similarly, aortic cross-clamping or side-clamping can be avoided by using proximal anastomotic devices during OPCABG. More recently, totally aortic *non-touch* techniques have been described that can be applied during OPCABG by using: (1) bilateral in situ internal mammary arteries; (2) sequential grafts; (3) in situ gastroepiploic arteries; (4) radial artery Y or T grafts from internal mammary arteries; (5) radial artery or vein grafts from innominate, subclavian, and axillary arteries; or (6) descending thoracic aorta. Currently, non-touch techniques during OPCABG are gaining popularity, especially in high-risk patients (Fig. 35.1). Nevertheless, given limited patient numbers and short follow-up times, the long-term graft patency rate for the latter procedures remains unknown.

Fig. 35.1 Totally aortic “non-touch” technique in off-pump three-vessel coronary artery bypass grafting surgery via left minithoracotomy; the inflow vein grafts come from the distal left subclavian artery in addition to in situ left internal mammary artery graft



35.5 Technological Innovations

New technologies have played a crucial role in the evolution of less invasive cardiac surgery. Importantly, they have changed the perceptions of cardiac surgeons regarding how cardiac surgery can or should be performed. With the help of new instruments specifically designed to meet the surgeon's need, less invasive cardiac surgical procedures once deemed impossible or impractical have now become reality, or even common practice, in some medical centers. These technological innovations have typically involved the following aspects of cardiac surgery.

35.5.1 Sternum-Sparing Surgery: Partial Sternotomy, Minithoracotomy, and Thoracoscopy

Major advances in this area include the development of a cardiopulmonary bypass support system via peripheral access. The application of suction to the venous drainage has made possible aortic valve and mitral valve surgery via partial sternotomy and minithoracotomy. An earlier breakthrough device in this field was the HeartPort system (developed by Stanford University and New York University Hospital in 1994) which was composed of peripheral vessel-based cardiopulmonary bypass perfusion, an endo aortic balloon occlusion catheter, transvenously placed venting and

cardioplegia cannulas, and extra-long operating instruments. Though its early use proved impractical in most cardiac operations, its potential to be less invasive has significantly changed cardiac surgeons' and medical engineers' perception of future technologies. Furthermore, the concept of the HeartPort system led to numerous other technological modifications and innovations in the field of less invasive cardiac surgery. Such innovations include: (1) the development of small caliber multistage peripheral venous cannula, (2) the safe application of vacuum-assisted venous drainage to ensure bloodless exposure inside heart, (3) the small thin blade minithoracotomy retractor and atrial retractor, (4) development of the Chitwood aortic cross-clamp, (5) thoracoscopy or endoscopic robotics to assist in the mitral valve repair or replacement, and (6) liberal use of transesophageal echocardiography to guide the insertion of various intracardiac cannulas.

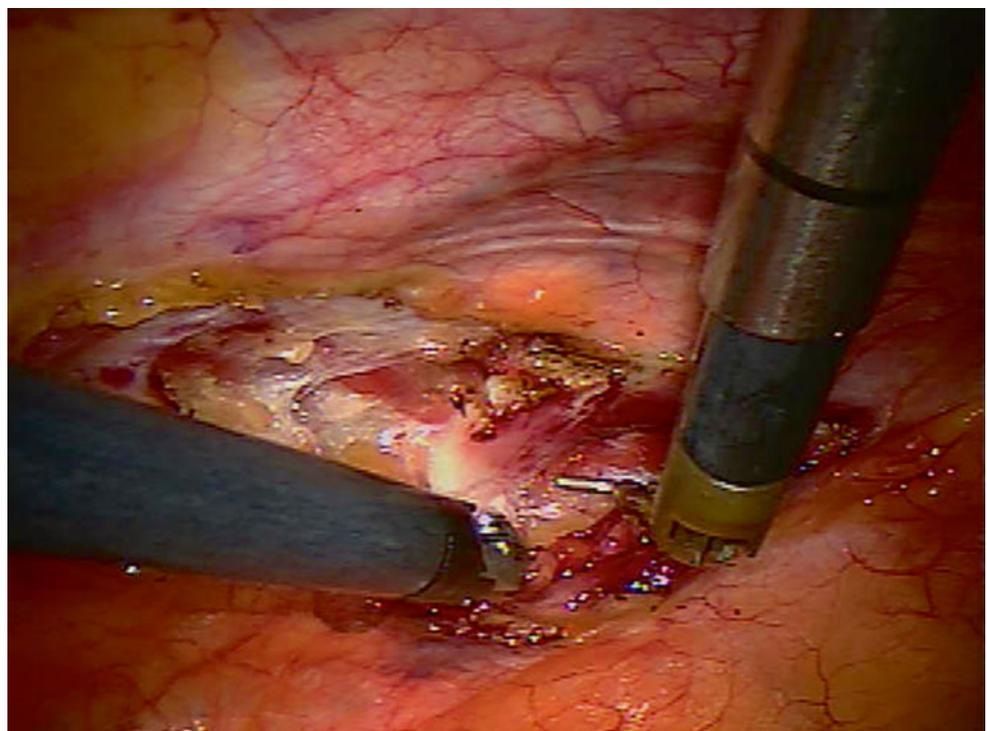
35.5.1.1 Upper Partial Sternotomy or Minithoracotomy Approaches for Aortic Valve Replacement

Currently more and more aortic valve replacements are performed via upper partial sternotomy or minithoracotomy. In such procedures, a limited partial sternotomy is made and the splitting of sternum is terminated at the 3rd or 4th intercostal space with either a “J” or inverted “T” incision, or a 6 cm incision is made at the right 2nd intercostal space (Fig. 35.2). Even an aortic valve replacement surgery can be performed via such a small incision, by using a combination

Fig. 35.2 Drawing of incisions used in minimally invasive aortic valve replacement. An upper sternotomy incision ends at the 3rd intercostal space at a “J” angle; a minithoracotomy incision is located at the right 2nd intercostal space



Fig. 35.3 The small incision allows for insertion of a combination of central and peripheral cannula for the establishment of cardiopulmonary bypass



of central and peripheral cardiopulmonary bypass circuits. Note that the aortic valve can be adequately exposed and replaced (Figs. 35.3 and 35.4).

A right minithoracotomy procedure is increasingly being used for minimally invasive mitral valve repair and/or replacement surgery. In these procedures, a 6 cm inci-

sion is typically made at the right 3rd intercostal space and a specially designed small retractor is inserted. A combination of central and peripheral cardiopulmonary bypass circuits is established, and intracardiac cannulas are inserted under the guidance of transesophageal echocardiography (Fig. 35.5). Currently, special instruments

Fig. 35.4 The exposure is adequate for aortic valve replacement. A bioprosthetic valve is visible



Fig. 35.5 A right minithoracotomy incision at the 3rd intercostal space. A combination of central and peripheral cannula insertion is used for the establishment of cardiopulmonary bypass



including clamps, scissors, forceps, and a knot-tying device are used for these procedures (Fig. 35.6). In other words, both mitral valve repair and replacement procedures can be safely performed using this approach

(Fig. 35.7). The main advantages of these procedures are decreased blood loss and the quick return of the patient to physical activities when compared to conventional sternotomy approach (Fig. 35.8).

Fig. 35.6 Special instruments with extra-long handles and small tips are used for minimally invasive mitral valve surgery

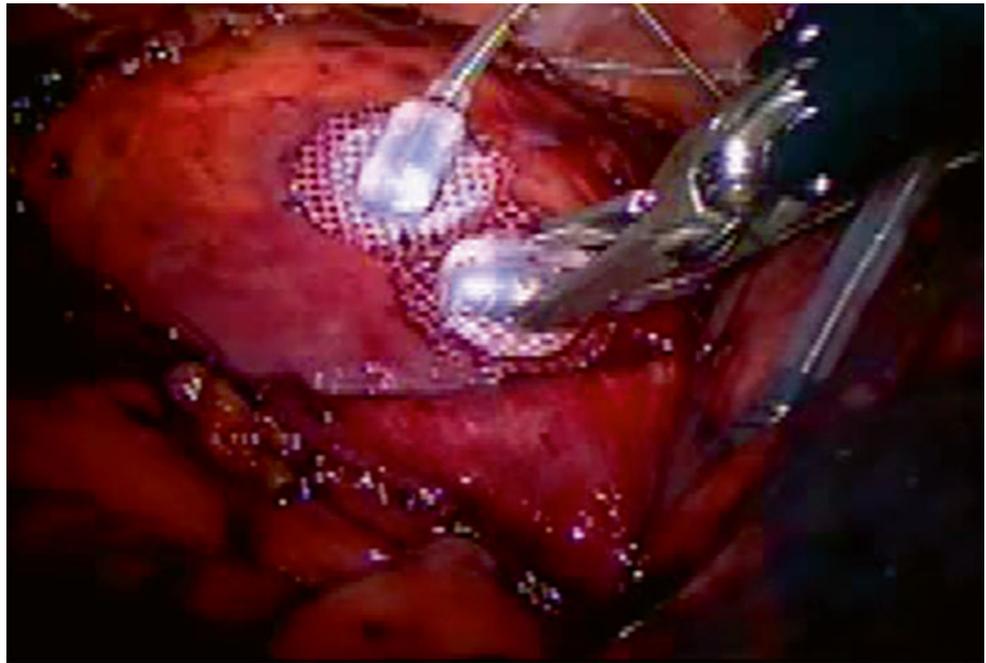


Fig. 35.7 Mitral valve repair with minithoracotomy can achieve good exposure



35.5.2 OPCABG Improvement

New instruments have also been developed to position the heart and to stabilize and improve the visualization of target arteries. For example, an available left ventricle suction device applies -400 mmHg suction to the left ventricular apex and can hold the heart up in different positions. Now

widely used in OPCABG surgery, this device has less of an effect on the venous return as compared with the old “suture retraction” technique. Similarly, a focal myocardial stabilization device has been developed to stabilize segments of target arteries; it has both suction and compressing effects on the topical epicardial tissue and thus significantly decreases the motion of target arteries (Fig. 35.9). An additional note-

Fig. 35.8 Minithoracotomy results in less blood loss, quick return to work, and a better cosmetic outcome



Fig. 35.9 An “octopus” myocardium-stabilizing device was used to steady the coronary artery during direct bypass grafting anastomosis

worthy device is the temporary intracoronary plastic shunt that can be inserted via arteriotomy to maintain blood flow to the distal myocardium during anastomosis, thus avoiding or minimizing ischemia time. Importantly, the use of such a shunt is considered to be crucial when the target artery supplies a large territory of myocardium. In order to facilitate the distal coronary anastomosis during OPCABG, especially in the anatomically difficult-to-reach areas, two innovative

distal coronary artery anastomotic devices, C-PortxA (for the open sternotomy approach) and C-Port Flex A™ (for the minithoracotomy or endoscopic robotic approach) (Cardica Inc., Redwood City, CA, USA), were developed and recently approved for clinical use by the FDA. It should be noted that although the early clinical results of such devices are encouraging [22], their clinical adaption has been lackluster.

35.5.3 Aortic Non-touch Techniques

Different proximal anastomotic devices or hand-sewn facilitators have been developed and used to avoid clamping on the aorta during OPCABG surgery. Unfortunately, the clinical performance of most of these devices has been unsatisfactory, resulting in denial of FDA approval or termination of the products after FDA approval, i.e., the previously FDA-approved symmetry (St. Jude Medical, St. Paul, MN, USA) automated proximal connector being one example.

Currently the Heartstring proximal seal system (Boston Scientific, Inc., Marlborough, MA, USA) is the only clinically available facilitator for proximal hand-sewn suture anastomosis. It temporarily occludes aortotomy during direct suture anastomosis of the proximal vein graft to the aortotomy; yet, to date, one of the major drawbacks of its use is that the suture can catch the device, which requires that the anastomosis be redone.

35.5.4 Endoscopic Robotics

Someday soon will operating rooms be devoid of cardiac surgeons? Perhaps, with the addition of robotics as a forefront technology. For example, Intuitive Surgical's da Vinci robotic system (Sunnyvale, CA, USA) has improved significantly in the past 15 years and has made operating inside the chest cavity possible. As of today, they have developed three generations of this technology; its 3rd generation, which is smaller and more user-friendly and has a "third arm" (one more arm than the 1st generation) and dual operating consoles for training purposes, has been recently available for clinical use. Its three-dimensional visualization, seven degrees of wrist motion, and capability to eliminate human hand tremors facilitate fine cutting and suturing tasks. For an increasing number of surgeons that are currently using this sophisticated machine, it has made both internal mammary artery takedown and OPCABG surgery via thoracoscopy or minithoracotomy easier (Fig. 35.10). Further, it has been described to have been used to repair atrial septal defects and mitral valves without sternotomy or thoracotomy. Currently, the employment of such systems will lead the way in moving toward total endoscopic CABG surgery (Figs. 35.11 and 35.12).

Nevertheless, complementary innovations have been required to allow for robotic surgery on the heart. For example, to make OPCABG surgery easier when it is performed via minithoracotomy or total endoscopic robotic approaches, an *endo suction device* and an *endo myocardium stabilizer* (Medtronic, Inc., Minneapolis, MN, USA) have been developed to position the heart and stabilize the target artery through port accesses.

The endoscopic robotic has greatly enhanced surgeons' ability to perform OPCABG via thoracoscopy and minithoracotomy. Robotic-assisted OPCABG performed at our institution and others [23] has shown the advantages of less pain, less blood loss, shorter length of stay, and fewer complications when compared to conventional CABG, especially in elderly high-risk patients. Another robotic application in cardiac surgery is mitral valve repair and replacement via thoracoscopy and minithoracotomy. When comparing robotic mitral surgery with standard sternotomy, major reductions in blood product utilization and length of stay are observed, while equivalence in complexity and success of mitral repairs is preserved [24]. Recent use of robotics to

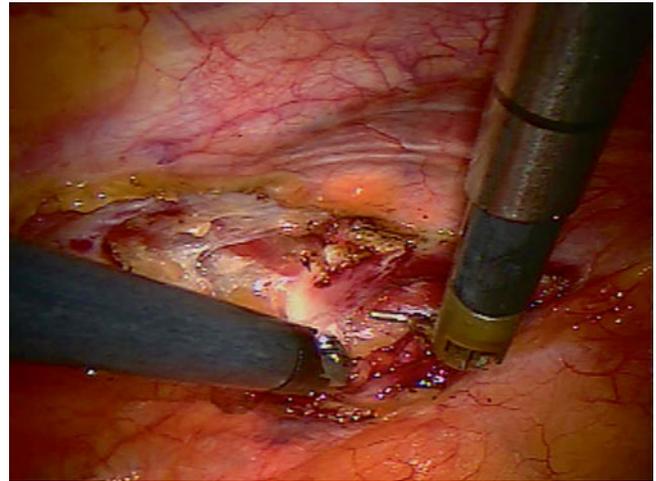


Fig. 35.10 Robotic arms operating inside the chest cavity to take down the left internal mammary artery

Fig. 35.11 Robotic arms in the operating room



Fig. 35.12 Surgeon is operating on the robotic console away from the patient

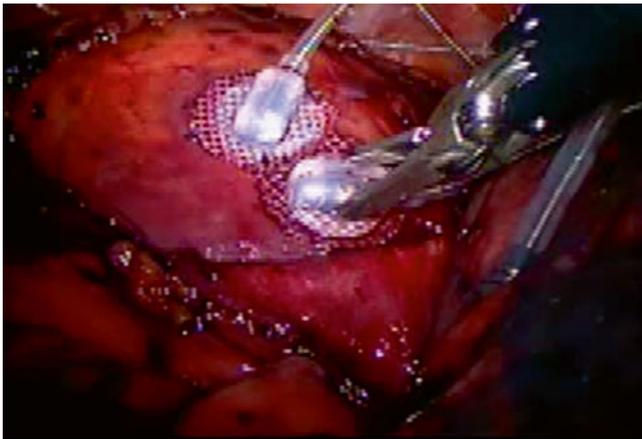


Fig. 35.13 Two left ventricular epicardial leads are placed by a robotic grasper in a patient who had previous coronary artery bypass grafting surgery



Fig. 35.14 Small incisions after multivessel off-pump sternum-sparing coronary artery bypass grafting surgery

implant left ventricular pacing leads as part of cardiac resynchronization therapy for congestive heart failure has shown the advantages of accuracy of locating the optimal pacing site and shorter procedure length compared to the cathlab percutaneous implantation (Fig. 35.13) [25].

35.6 Future Directions

The ultimate goal of less invasive cardiac surgery is to avoid cardiopulmonary bypass support and sternotomy and rather to perform surgery through tiny incisions. Various specially designed instruments are still being developed to make such procedures possible, including: (1) automated proximal and

distal CABG anastomotic devices, (2) the endo myocardium stabilizer, (3) the endo suture device, and (4) the endo vascular clamp. The da Vinci surgical robotic system has enabled the use of such instruments inside the closed chest cavity. It is likely that in the very near future, cardiac surgery will be performed utilizing only three to four key holes in the chest wall (Fig. 35.14).

The following cardiac procedures will likely advance in the near future with regard to the less invasive approaches: (1) total endoscopic robotic OPCABG using single or bilateral in situ internal mammary artery, with the help of flexible distal coronary artery anastomotic devices; (2) hybrid robotic-assisted OPCABG and percutaneous stenting in the hybrid operating room or hybrid CathLab (Fig. 35.15);

Fig. 35.15 Surgeon is performing robotic-assisted hybrid surgery in the CathLab



(3) total endoscopic robotic mitral valve repair; (4) increased the use of robotic-assisted left ventricular pacing lead implantation or hybrid electrophysiology ablation therapy; and (5) aortic valve replacement via percutaneous or transapical approaches in the hybrid operating room or CathLab.

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