MINIMALLY INVASIVE CARDIOVASCULAR SURGERY: INCISIONS AND APPROACHES

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Abstract

Throughout the modern era of cardiac surgery, most operations have been performed via median sternotomy with cardiopulmonary bypass. This paradigm is changing, however, as cardiovascular surgery is increasingly adopting minimally invasive techniques. Advances in patient evaluation, instrumentation, and operative technique have allowed surgeons to perform a wide variety of complex operations through smaller incisions and, in some cases, without cardiopulmonary bypass. With patients desiring less invasive operations and the literature supporting decreased blood loss, shorter hospital length of stay, improved postoperative pain, and better cosmesis, minimally invasive cardiac surgery should be widely practiced. Here, we review the incisions and approaches currently used in minimally invasive cardiovascular surgery.

Introduction

Along with the broader surgical community, cardiovascular surgery is in the midst of an ongoing evolution in technique. What began in the 1990s with the first reports of minimally invasive valve surgery has spread to influence nearly every type of cardiovascular operation performed today, and this evolution is being further spurred by recent developments in percutaneous valve technology. With increasing patient interest in minimally invasive procedures, it is more important than ever for surgeons to be current on the most common minimally invasive techniques in cardiac surgery. Herein, we will review the most widely used incisions and approaches, with a focus on aortic valve, mitral valve, and coronary artery bypass procedures.

Aortic Valve Approaches

Aortic valve disease is a common indication for cardiac surgery, with the prevalence of aortic stenosis rising to nearly 10% in patients aged 80 years and older.[1] Consequently, the need for surgery to treat aortic stenosis will likely increase as the population ages and continue to be a significant part of all cardiac surgical practices. Minimally invasive approaches to the aortic valve have evolved significantly since the first reports in the 1990s and today are safely and consistently performed at many centers.[2-4] While available evidence is retrospective, multiple series have reported decreases in bleeding, duration of mechanical ventilation, intensive care unit length of stay, overall hospital length of stay, and postoperative pain in patients undergoing minimally invasive aortic valve surgery compared to those receiving a standard median sternotomy.[5-11]

Hemisternotomy

While minimally invasive approaches to the aortic valve can be accomplished with a wide range of incisions, the most commonly used approach is a hemisternotomy, usually extended in a J-shape into the right fourth intercostal space. In this technique, a midline incision is made at the sternomanubrial junction and extended inferiorly 4 to 5 cm. The necessary sternal exposure can be achieved without enlarging the skin incision by undermining the soft tissue both superiorly and inferiorly. Next, a standard sternal saw is used to divide the sternum in the midline until gently curving to enter the fourth intercostal space.

While extending the incision into the fourth intercostal space is the most common approach, the specific intercostal space used can and should be tailored to the patient. For example, appropriate exposure may be possible using the third intercostal space in a thin patient while the fifth space may be required in an obese patient. Exposure of the aortic root is also possible when the sternotomy is carried into the fifth intercostal space, making this a useful approach in a wide range of aortic valve and aortic root operations (Figure 1). Once the sternum is divided and mediastinal tissues dissected, a vertical pericardiotomy is made and the edges of the pericardium are sutured to the skin. This allows full anterior retraction of the mediastinum and maximizes exposure of the aorta.

One advantage of the hemisternotomy approach is that it allows for a variety of different cannulation strategies, ranging from entirely central to purely peripheral. At Columbia University Medical Center, we prefer using the standard, centrally-placed ascending aortic and right atrial cannulas along with a right superior pulmonary vein vent and, if desired, a retrograde cardioplegia catheter. Since this strategy is identical to that used in a full sternotomy operation, it minimizes the new techniques that must be learned to successfully perform the procedure. Exposure and visualization can be maximized by retracting the venous cannula inferolaterally with a suture passed through the chest wall using a needle-hook device, using lower profile aortic cross clamps, and placing the patient in the steep reverse Trendelenburg position. However, cannulation can also be performed via the femoral artery and vein, with the pulmonary artery vent or retrograde cardioplegia catheter placed peripherally from the neck. Entirely peripheral cannulation minimizes potential obstructions within the operating field but requires significant experience on the part of the anesthesia and perfusion teams; consequently, it is not feasible at many centers. In our experience, retraction of cannulas to the periphery of the field provides adequate visualization and working space without the additional technical challenges presented by peripheral cannulation. Once cannulation is achieved, the remainder of the operation is performed in the standard fashion.

Figure 1. Hemisternotomy incision 4 weeks following a minimally invasive aortic valve replacement.

Right Anterior Thoracotomy

Another minimally invasive approach to the aortic valve is the right anterior thoracotomy (RAT).[12] This procedure is more commonly used for operations on the mitral valve (see below), but RAT can be used for aortic valve surgery as well. Although this approach avoids sternotomy, it provides inferior exposure in most cases since the aortic root and valve are more difficult to see and reach from this angle. Additionally, RAT usually requires more sophisticated and active transesophageal echocardiogram (TEE) guidance, at the very least for peripheral cannulation and in some cases for peripheral insertion of retrograde cardioplegia catheters or pulmonary vein vents. As discussed previously, this requires specific expertise on the part of the anesthesia and perfusion teams.

With RAT, a 4- to 6-cm incision is made over the medial aspect of the right third intercostal space, the underlying tissue is dissected, and the pleural space is entered. Due to the very medial incision, the right internal mammary vessels usually require ligation at this stage, and the third or fourth rib may also need to be disarticulated from the sternum to provide adequate exposure. The pericardium is then opened anterior to the phrenic nerve, and the pericardiotomy is carried to the diaphragm inferiorly and pericardial reflection superiorly. An antegrade cardioplegia cannula is placed directly through the primary incision, and a transthoracic aortic cross-clamp is inserted via a stab incision. From this point the operation is performed in the standard fashion, after which sutures are used to reattach the disarticulated rib to the sternum. Considering the frequent need for costochondral disarticulation and the rib fractures often associated with this approach, we favor the hemisternotomy, which results in less pain.

Mitral Valve Approaches

In their pioneering cases, Cohn, Navia, and Cosgrove used a right parasternal approach for minimally invasive mitral valve surgery.[2,13] Several years later, Mohr and Chitwood reported the first mitral valve cases performed through a right thoracotomy.[14,15] Since that time, alternative approaches such as hemisternotomy, left thoracotomy, and right minithoracotomy have been developed; of those, the right minithoracotomy is the most widely used in current clinical practice.

Right Minithoracotomy

The right minithoracotomy has been established as the most commonly used incision for minimally invasive mitral valve surgery and is now the standard minimally invasive approach at most centers. Multiple retrospective series have assessed outcomes following mitral valve surgery via right minithoracotomy, with reported advantages including a more en face view of the valve, a decreased risk of infection due to the well-vascularized overlying pectoralis muscle and avoidance of sternal division, shorter hospital length of stay, decreased postoperative bleeding, and improved postoperative pain.[16-19]

To approach the mitral valve via a right minithoracotomy, a 4- to 6-cm inframammary incision is made in the midaxillary line for primary access and augmented as needed with stab incisions. This primary incision is made 1 to 2 cm inferior to the nipple in men and about 1 cm above the breast crease in women, with subsequent soft tissue dissection directed cephalad towards the chest wall to allow entry into the thoracic cavity through the fourth intercostal space (Figures 2, 3). The incision is typically made medially to minimize the working distance to the valve but not nearly as medially as for aortic valve surgery. In fact, moving the incision a bit laterally results in a more en face view of the valve but at the cost of greater distance from the surface. The ideal location to maximize working distance and valve visualization can be modified according to surgeon preference.

Once the primary incision is made, stab incisions are used to introduce supporting instruments. In our practice, two small stab incisions are made a few intercostal spaces below the primary incision for passage of a carbon dioxide insufflator and pump sucker during the procedure and chest tubes after. If desired, a 5- or 8-mm

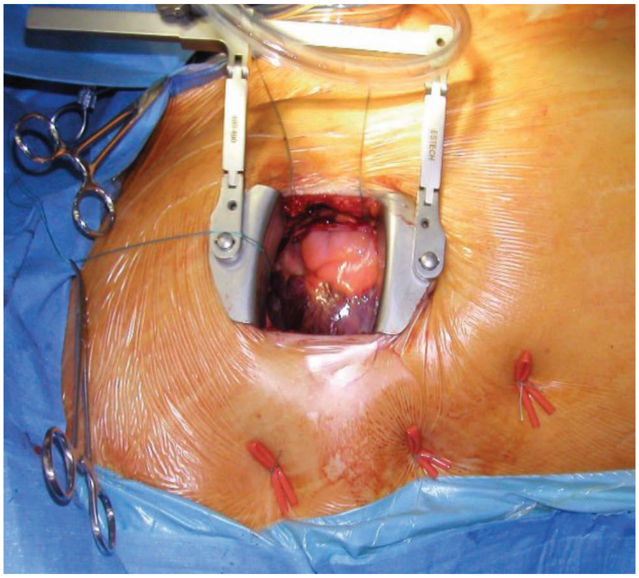

Figure 2. Exposure for minimally invasive mitral valve repair via a right minithoracotomy.

Figure 3. A young woman 4 weeks after mitral valve repair through a right minithoracotomy.

videoscope can be introduced through one or more of these incisions, both of which are in the anterior axillary line. To improve exposure of the heart, the right hemidiaphragm is retracted inferiorly by placing a suture in its tendinous dome and bringing it out to the skin through the seventh or eighth interspace using a needle-hook device.

Next, the pericardium is opened starting several centimeters anterior to the right phrenic nerve, and the pericardiotomy is extended inferiorly to the diaphragm and superiorly to the ascending aorta. The anterior edge of the pericardium is retracted with sutures to the medial portion of the skin incision and the posterior edge retracted with a suture brought to the skin with the needle hook. A transthoracic Chitwood clamp is then inserted through a stab wound in the third interspace in the right midaxillary line, and preparations for eventual atrial retraction are made by introducing a retractor through the chest wall medial to the primary incision. This retractor can be self-retaining, as in devices that attach directly to the chest wall with screw-clamp mechanisms, or can be held in place by table-mounted clamps.

While cannulation for cardiopulmonary bypass can be performed with an entirely peripheral strategy, at Columbia University Medical Center we prefer to use as much central cannulation as possible. Similar to minimally invasive aortic surgery, utilizing central cannulation minimizes both the number of new techniques needed to adopt the overall procedure and the expertise required of other members of the operating room team, such as anesthesia and perfusion. In particular, avoiding peripheral arterial cannulation and endoaortic balloon occlusion not only simplifies and shortens the procedure but also eliminates the risk of complications such as retrograde aortic dissection, retroperitoneal hemorrhage, and lower limb ischemia.

With a minithoracotomy, it is possible to place the aortic, superior vena caval, antegrade cardioplegia, and retrograde cardioplegia cannulas centrally through the primary incision, leaving only the inferior vena caval cannula to be placed peripherally. We insert a multistage venous cannula through the femoral vein using a Seldinger technique under TEE guidance, supplemented as needed by a standard right-angle cannula placed through the primary incision into the superior vena cava. While this degree of central cannulation decreases technical difficulty and simplifies the overall process, it does create the potential for obstructed visualization or movement during the procedure. Alternative cannulation strategies include an entirely peripheral and a hybrid design, where the aortic and venous cannulas are peripheral and the antegrade and retrograde cardioplegia cannulas remain central.

Once the patient is cannulated and cardiopulmonary bypass begun, exposure of the mitral valve can commence with dissection of Sondergaard's groove. After aortic cross clamping, the left atrium is opened and the anterior left atrium and septum are retracted anteriorly using one of the retractor types described above. One maneuver that helps maximize visualization is placement of a retraction suture (we use 3-0 monofilament) about a centimeter away from the P3 portion of the mitral annulus in the inferior left atrial wall. This suture is then passed out of the left atrium, behind the inferior vena cava (through the oblique sinus), and out of the chest laterally. This serves to both retract the redundant inferior left atrial wall away from the valve and also to pull the inferior portion of the valve into better view. Another trick is placing the transthoracic retractor as close to the sternum as possible to prevent the left atrium from slipping off the retractor and away from the surgeon. In doing this, special attention should be paid to the left internal mammary artery, which can be injured by this maneuver. Finally, the valve can be brought several centimeters closer to the surgeon by placing a few heavy sutures in the posterior mitral annulus, as is done during annuloplasty, and clamping them to the surgical drapes. Once exposed, valve repair or replacement is performed in the standard manner. Many surgeons have found manual knot-pushing instruments and even newer automatic knot-tying devices to be helpful in these cases, although we prefer to use old-fashioned finger tying. This is almost always possible if the exposure is established correctly. Upon completion of the valve repair or replacement, the atriotomy is closed in the standard fashion and the heart de-aired under TEE guidance.

There is much discussion on the subject of de-airing in minimally invasive surgery. Our routine is to use carbon dioxide insufflation throughout every case, followed by an extensive de-airing protocol performed under TEE surveillance. This includes positioning the patient in deep Trendelenburg during aortic unclamping, aggressive volume loading of the heart, positive-pressure ventilation to clear pulmonary venous air, and alternation of left-right table positioning to remove air trapped under the ventricular septum. After de-airing, pacing wires are placed, a local nerve block is applied, and the chest is closed. To avoid late lung herniation, we close the ribs with heavy (#5) nonabsorbable braided pericostal sutures followed by layers of absorbable sutures. It is important to avoid closing the intermediate soft tissue layers too tightly, which can give the wound a puckered look. Of note, this approach is also used at our center for a variety of other cardiac procedures, including tricuspid valve surgery, atrial septal defect repair, cardiac tumor resection, and atrial fibrillation surgery.

Robotic Mitral Valve Surgery

The development of telemanipulation technology during the 1990s paved the way for robotic-assisted valve surgery, and in 1998, Carpentier and Mohr independently reported the first cases of robotic mitral valve repair.[14,20] The technique evolved rapidly, and over the next 2 years, Mehmnesh and colleagues performed the first closed-chest endoscopic mitral valve repair, Grossi and associates performed a posterior leaflet repair, and Chitwood and colleagues performed a posterior leaflet resection with subsequent reconstruction and ring annuloplasty.[21-23] In addition to the potential benefits of minimally invasive surgery, numerous groups have reported further advantages of robotic surgery, including 3-dimensional visualization, ambidexterity, tremor filtration, motion scaling, and even smaller incisions.[24-26] Outcomes following robotic mitral valve surgery in a prospective, multicenter, phase II trial of 112 patients showed an 8% rate of postoperative grade 2 mitral regurgitation and a 5.4% reoperation rate.[27]

At Columbia University Medical Center, we participated in the first U.S. trial of robotic mitral valve surgery and currently perform the procedure, as developed by Chitwood, through a 5- to 6-cm submammary right minithoracotomy that enters the chest through the fourth intercostal space. This incision is similar to that used in the minithoracotomy approach described previously, and intrathoracic preparations are carried out at our center in the same manner. Cannulation for cardiopulmonary bypass can be peripheral or central, as previously discussed. Aortic occlusion can be performed with either a transthoracic aortic cross-clamp or an endoaortic balloon, and carbon dioxide insufflation of the operative field is continuous.

Generally, two robotic arms are inserted into the chest through 10-mm trocar incisions. The right instrument is inserted 4- to 6-cm lateral to the thoracotomy in the fourth or fifth intercostal space, and the left instrument is placed medial and cephalad to the right instrument in the second or third intercostal space. A distance of 6 cm is maintained between the arms, and the alignment of the arms with the valve plane is optimized to allow unrestricted movement of the instruments. A 30-degree stereoscopic endoscope is inserted through the medial portion of the thoracotomy, leaving the remainder of the incision as a working port for the patient-side assistant. A third arm can also be used as a dynamic retractor, if desired.[26] Once the patient is on cardiopulmonary bypass, the left atrium is accessed using an interatrial groove left atriotomy, and the valve is exposed with a transthoracic intra-atrial retractor. Valve repair, atriotomy closure, weaning from cardiopulmonary bypass, de-airing, and closure can then proceed in the usual fashion. Of note, while there have been reports of nitinol clips used in place of robotically-tied sutures for fixing annuloplasty rings or bands, many centers continue to use sutures.[28]

Coronary Artery Bypass Grafting

While coronary artery bypass grafting (CABG) remains the gold standard for coronary revascularization, it continues to be performed primarily through a median sternotomy, with little change in the overall invasiveness of the procedure. This is due to several factors that make CABG more complicated when performed through small incisions, including the technical demands of delicate vascular dissection and suturing, the difficulty of exposing multiple areas of the heart, internal mammary arteries, and aorta, and prolonged operating times.[29] Despite these challenges, experience in minimally invasive CABG is growing.

Totally Endoscopic CABG

One potential approach, first reported by Loulmet and Falk, is totally endoscopic coronary artery bypass grafting (TECAB) using robotic surgery systems.[30,31] This technique allows the surgeon to harvest the left internal mammary artery (LIMA) and perform an anastomosis to the left anterior descending artery (LAD) without median sternotomy. In a prospective, multicenter study that was the first to evaluate the efficacy and safety of TECAB and ultimately led to FDA approval of this procedure, Argenziano and colleagues found 91% freedom from graft failure at 3 months and a 5.9% rate of major adverse cardiac events, which is less than reported in patients undergoing single-vessel CABG via median sternotomy in the Society for Thoracic Surgery database.[32]

As described by Loulmet et al, TECAB is performed using a robotic surgical system with three arms inserted into the thoracic cavity.[30] After single lung ventilation and carbon dioxide chest insufflation are established, the first arm is inserted through the fourth intercostal space at the midclavicular line so it faces the anastomotic site and allows visualization of the entire length of the LIMA. The second arm is then inserted through the third or fourth intercostal space at the anterior axillary line so that the right-hand instruments can reach the middle third of the LAD and both ends of the LIMA. Lastly, the third arm is inserted through the sixth or seventh intercostal space at the anterior axillary line so that the left-handed instruments can also reach the middle third of the LAD and both ends of the LIMA.

After all instruments are appropriately placed, the LIMA is harvested in its entirety and preparations made for cardiopulmonary bypass. In TECAB, cannulation is entirely peripheral and is achieved, using TEE guidance, with an endoaortic balloon cannula inserted via the femoral artery and a single venous cannula inserted into the femoral vein and advanced into the right atrium. Once the balloon is inflated to effectively cross-clamp the aorta, antegrade cardioplegia is given and the distal LIMA-to-LAD anastomosis performed robotically. After completion of the anastomosis, the balloon is deflated, the patient is weaned from cardiopulmonary bypass, and the port sites are closed in the standard fashion.

The TECAB procedure has some significant restrictions, including the need for peripheral cardiopulmonary bypass and its limitation to only single-vessel CABG in most centers. However, several groups have published case series that include multivessel TECAB. Srivastava and colleagues reported successful multivessel beating heart TECAB with bilateral mammary harvest in 73 patients by using positioning and tissue-stabilizing devices via two additional ports.[33] In a retrospective multicenter series of 500 total patients, Bonaros and associates described 166 arrested- and beating-heart multivessel TECAB cases performed using four ports, also with tissue-stabilizing devices.[34] Srivastava also reported a series of 150 patients who underwent robotic-assisted multivessel CABG with totally endoscopic bilateral internal mammary artery harvest followed by proximal and distal anastomoses through a 6- to 10-cm lateral thoracotomy in the fifth interspace.[35]

Minimally Invasive Direct Coronary Artery Bypass

An alternative minimally invasive technique that does not require a surgical robot is minimally invasive direct coronary artery bypass (MIDCAB), a broad term for CABG performed without median sternotomy. MIDCAB most often entails either single or multivessel CABG through a small thoracotomy, usually without cardiopulmonary bypass. One approach, as described by McGinn and colleagues, uses a 4- to 7-cm anterolateral thoracotomy in the fifth intercostal space.[36] This allows the LIMA to be harvested from a lateral approach under direct vision. Next, 6-mm incisions are made in the subxyphoid area and seventh intercostal space, through which an apical positioning device and

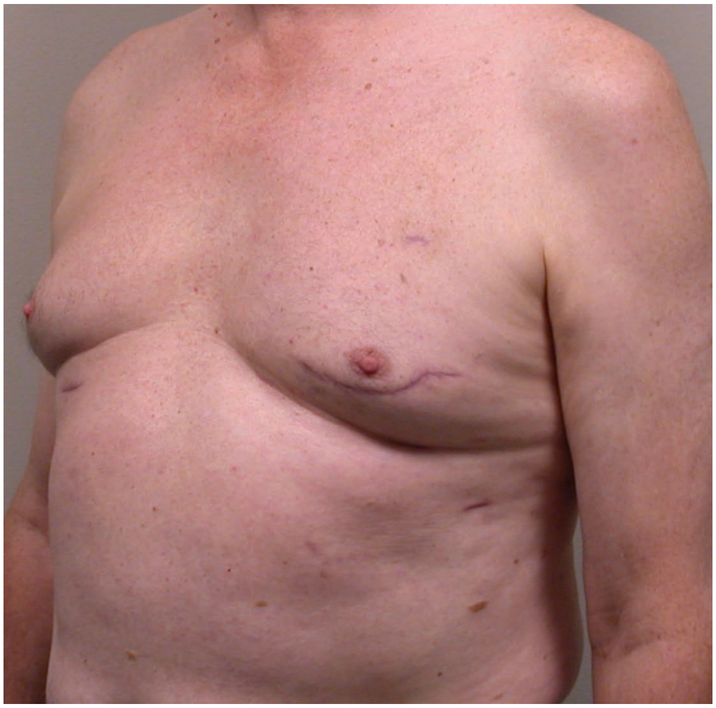

Figure 4. Postoperative photo 2 weeks after off-pump double coronary bypass performed through left minithoracotomy.

epicardial tissue stabilizer are placed to facilitate exposure of all coronary artery territories. The distal and proximal anastomoses can then be hand-sewn with the heart beating unless the exposure is inadequate or the patient does not tolerate the required heart positioning, in which case cardiopulmonary bypass can be instituted with peripheral cannulas placed via the femoral vessels. A limitation of this approach is that it does not allow for bilateral internal mammary artery harvest without the use of a thoracoscope, an additional right thoracotomy, or a surgical robot.

At our center, robotically assisted MIDCAB uses selective lung ventilation via double-lumen endotracheal intubation, followed by robotic harvest of the LIMA via three port incisions (Figure 4). Once the LIMA is prepared, the center port, which is located in the fifth intercostal space in the midaxillary line, is converted to a 5-cm minithoracotomy. Next, a small rib retractor is positioned, and after the pericardiotomy and identification of the target coronary artery, a proprietary suction stabilizer is passed through the inferior port incision and held by an attachment to the rib retractor (Figure 5). This allows the use of standard off-pump CABG techniques, as there are no obstructions to visualization through the primary incision.

Overall, the application of minimally invasive techniques to CABG continues to increase; however, they are still used primarily by specialized centers. Given the significant technical challenges involved, further improvement in both training and technique are needed to allow for wider adoption.

Conclusion

Since the pioneering cases of the 1990s, minimally invasive techniques have been applied to a wide range of cardiac procedures. In the intervening 2 decades, numerous reports in the literature have demonstrated the feasibility, safety, and efficacy of minimally invasive cardiac surgery and supported its integration into clinical practice. With increasing patient demand for less invasive surgical options and the ongoing development of percutaneous technologies, it is essential that cardiovascular surgeons remain familiar with the most widely used approaches. In the future, the continued evolution of endoscopic, robotic, and percutaneous technologies will only increase the ability of surgeons to address cardiovascular disease with decreasing operative trauma.

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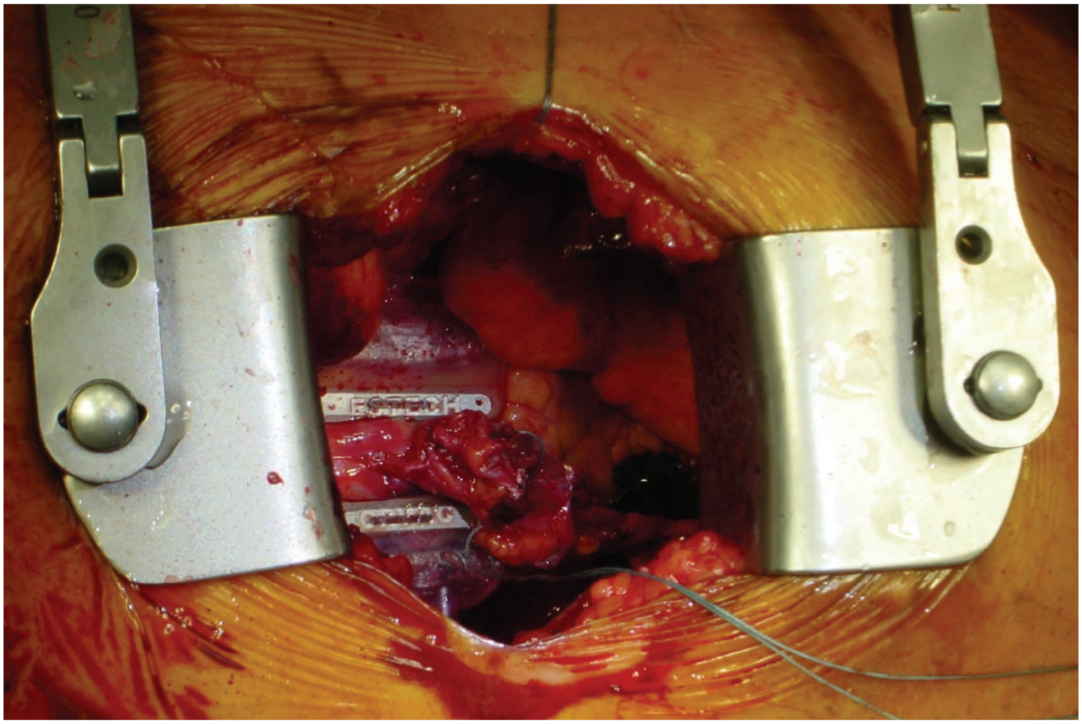

Figure 5. Exposure for a minimally invasive direct coronary artery bypass performed using a left minithoracotomy, with coronary target stabilization using a retractor-mounted, low-profile suction stabilizer.

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