Artificial
Organs

Review Article

Minimally Invasive Ventricular Assist Device Surgery

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Abstract: The use of mechanical circulatory support to treat patients with congestive heart failure has grown enormously, recently surpassing the number of annual heart transplants worldwide. The current generation of left ventricular assist devices (LVADs), as compared with older devices, is characterized by improved technologies and reduced size. The result is that minimally invasive surgery is now possible for the implantation, explantation, and exchange of LVADs. Minimally invasive procedures improve surgical outcome; for example, they lower the rates of operative complications (such as bleeding or wound infection). The miniaturization of LVADs will continue, so that minimally invasive techniques will be used for most implantations in the future. In this article, we summarize and describe minimally invasive state-of-the-art implantation techniques, with a focus on the most common LVAD systems in adults. **Key Words:** Left ventricular assist device—Minimally invasive surgery—Cardiac surgery.

In the United States and Europe, the annual incidence of chronic heart failure ranges from 0.3% to 1.0%. The condition remains a major problem in developed countries, especially with population growth and the increase in mean weight and age (1). According to the latest surveys, the annual death toll from cardiovascular disease is about 810 000 people in the United States and 12.2 million people worldwide (2). Recent projections estimate that ischemic heart disease will remain the major cause of death until 2030 (3).

In recent years, medical therapy has improved outcomes for patients with mild to moderate heart failure (4). However, patients with progressive heart failure refractory to optimized drug therapy require further therapeutic strategies, such as a heart transplant or mechanical circulatory support (5–9). In the 1960s, Norman E. Shumway, a surgical pioneer at Stanford University, paved the way for the long-term success of heart transplants in humans (10). His fellow student at the University of Minnesota, Christiaan N. Barnard, performed the world's first human heart transplant in 1967 in South Africa (11). Since then, more than 100 000 human heart transplants have been performed worldwide (12,13).

In the United States, more than 2000 heart transplants are now performed each year. However, the number of transplants is limited by the severe donor shortage, which is causing mortality rates of about 30% on the waiting lists. Additionally, since the mid-1980s, the total number of transplanted hearts has been decreasing (12).

Regenerative approaches for treating patients with end-stage heart disease, such as the use of stem cells (14–19) or tissue engineering (20), are still in development. Mechanical circulatory support is currently the most promising alternative to a heart transplant for patients with terminal heart failure (21–25). Since the first implantation of a left ventricular assist device (LVAD) in the 1960s by Michael E. DeBakey (26),

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this field has experienced enormous advances (9). In the past, the use of older extracorporeal devices forced patients to be bedridden and was possible for merely a short period as a bridge to transplant, involving several risks; only the most critically ill patients could be treated with such devices. However, during the past decade, the use of the newest generation of implantable continuous-flow LVADs incorporating improved pump technologies has resulted in lower complication rates and in excellent long-term durability (21,22,27,28). LVADs are now used as destination therapy in nonterminal patients, including those whose status is classified as level 4 or higher by the Interagency Registry for Mechanically Assisted Circulatory Support (INTERMACS) (29). In fact, the worldwide number of LVADs implanted per year is now higher than the number of heart transplants.

Next to technical improvements, the most significant advance in LVADs has been their considerable miniaturization, which has allowed the use of minimally invasive techniques in the implantation (24), explantation (30), and exchange of LVADs (31). In this article, we summarize our MEDLINE review of the existing literature and describe minimally invasive, state-of-the-art implantation techniques, with a focus on the most common LVAD systems in adults.

METHODS

We performed a systematic literature review using MEDLINE. The search strategy combined the following terms: "ventricular assist device," "mechanical circulatory support," "less invasive," and "minimally invasive."

RESULTS

The most common LVAD implantation techniques and products in adults and the most concerning issues, as determined by our literature review and analysis, are described below.

Standard approach

The standard implantation approach for modern LVAD systems is through a full sternotomy with right-atrial and aortic cannulation for the heart–lung machine (21,22,25) (Fig. 1). Major disadvantages of this approach are a significant incidence of postoperative bleeding, sternal instability, wound infections, and right heart failure (32).

HeartMate II by Thoratec

Hill et al. introduced the concept of less invasive implantation in three patients receiving the paracorporeal Thoratec LVAD (Thoratec Corp., Pleasanton, CA, USA) (33) (Fig. 2A). They advocated a combination of a right mini-thoracotomy and a left subcostal incision. Of three LVAD patients with dilated cardiomyopathy, two experienced postoperative bleeding and needed drainage (by chest tubes) and blood transfusions. One patient died (for technically unrelated reasons), but the other two were able to safely undergo a heart transplant.

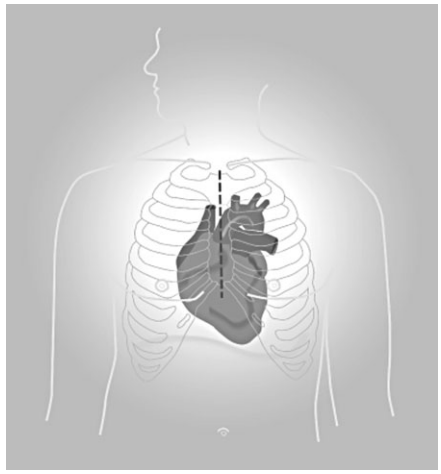

FIG. 1. Conventional LVAD implantation approach. This standard surgical technique is currently the most popular LVAD implantation approach. However, it involves important disadvantages such as increased bleeding, sternal instability, and wound infections.

After those early results reported by Hill et al., the new minimally invasive technique was applied by other groups using new-generation devices, with significant improvements. Gregoric et al. described a less invasive approach for implanting the Thoratec HeartMate II LVAD (34) (Fig. 2C). They advocated a subcostal incision, followed by separating the interfering muscles (stopping extraperitoneally above the transverse muscle fascia). Then, the pleura was opened in order to allow access to the pericardium and the left ventricular apex below. Before LVAD placement, a subcostal pocket had to be created for the pump housing. A parasternal mini-thoracotomy on the third right intercostal space was done in order to perform the aortic anastomosis of the outflow graft. Overall, Gregoric et al. performed the procedure successfully in three patients (34).

More recently, Anyanwu et al. also successfully applied this sternotomy-avoiding technique with minor modifications (35). Samuels et al. used a less invasive approach including an upper hemisternotomy, a left-sided lateral thoracotomy, and a partial-midline upper abdominal preperitoneal laparotomy;

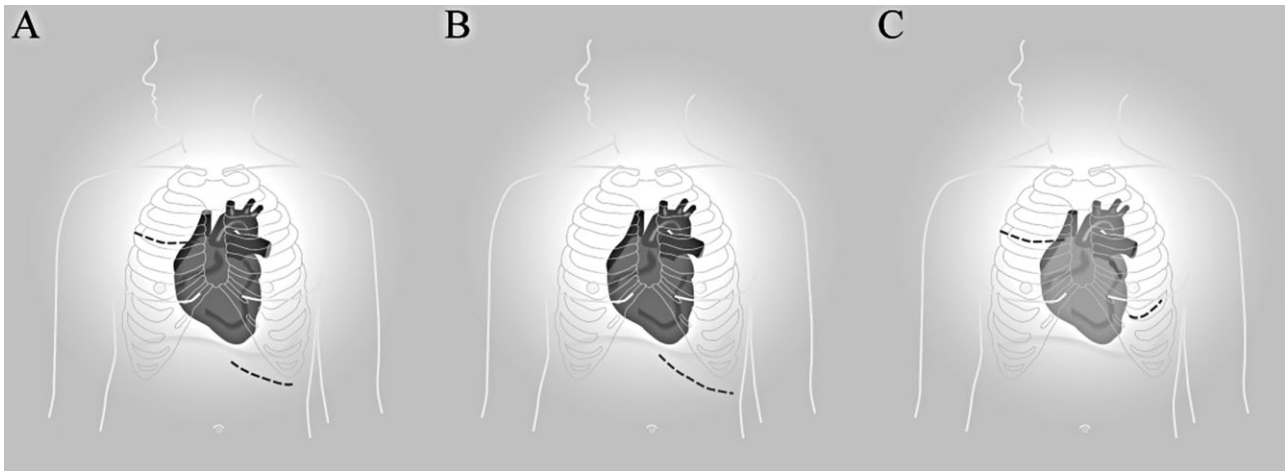

FIG. 2. First steps toward a minimally invasive LVAD implantation. (A) Hill et al. developed a two-stage approach for first-generation LVADs. Due to the increased size, a subcostal incision was needed for abdominal pump placement. (B) An alternative approach developed by Frazier et al. for the Jarvik 2000 Heart was the first one to avoid a sternotomy. Still, the pump had to be placed in a subcostal pocket. The outflow graft was then anastomosed to the descending aorta. (C) The current generation of LVAD systems allows changing the subcostal incision with a left-sided thoracotomy for pump insertion.

the upper preperitoneal incision created the LVAD pocket in the subrectus muscle plane, while two lateral dissections connected to both inflow and outflow pathways (36). An alternative approach was described by Riebandt et al. from Vienna: In the setting of severe thoracic aortic calcification, they anastomosed the outflow graft to the right subclavian artery (37).

HVAD by HeartWare

The minimally invasive approach to the implantation of the HeartWare ventricular assist device (HVAD) (HeartWare International, Inc., Framingham, MA, USA) was developed at Hannover Medical School in Hannover, Germany (15) (Fig. 3A). Sometimes called the "Hannover technique," it was further modified in the London-Harefield and Vancouver techniques (24,38,39). This technique combines an upper hemisternotomy with a left-sided anterolateral thoracotomy, as introduced by Schmitto et al. (24,38) (Fig. 3A). First, the patient is placed on cardiopulmonary bypass, using venous cannulation into the right femoral vein and arterial cannulation into the ascending aorta via an upper hemisternotomy. By avoiding a full sternotomy, the surgeon can keep the pericardium mainly closed, preserving the natural right ventricular delimitations and thereby avoiding right ventricular dilatation during LVAD implantation. Thus, right ventricular function remains passively sustained (24). Second, an anterolateral thoracotomy is performed, and an epicardial HVAD sewing ring is implanted on the left

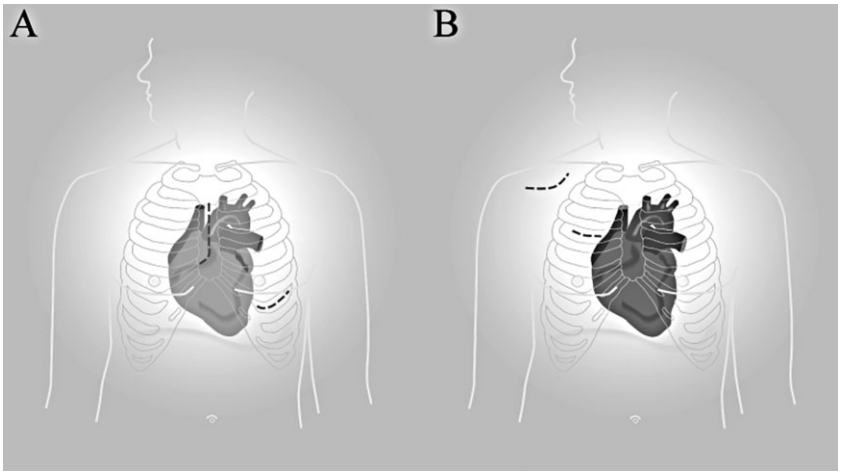

FIG. 3. Minimally invasive LVAD implantation. (A) The combination of a J-shaped hemisternotomy with a left-sided thoracotomy, also known as the Hannover technique, was described by Schmitto et al. It avoids extrathoracic incisions and reduces perioperative bleeding incidence, infection risks, and right heart impairment. (B) Partial left ventricular support enables reduced pump sizes as compared with full-support systems. Thus, these pumps can be placed in a subclavian position, similar to a pacemaker. While the inflow is placed in the left atrium, the outflow graft is anastomosed to the right subclavian artery.

ventricular apex. Then, the HVAD pump is placed through the sewing ring into the left ventricular apex. The outflow graft is tunneled through the pericardium and then anastomosed end-to-side to the ascending aorta through the upper hemisternotomy. The driveline is placed in the sheath of the rectus muscle in the umbilical direction and then subcutaneously to the right or left upper quadrant. This approach enlarges the subcutaneous driveline course, decreasing infection rates (40).

After de-airing the device, the pump is started in situ. The pump speed must be gradually increased while the patient is weaned from the extracorporeal circulation. A mean pump flow of 5 ± 0.5 liters is usually achieved when the left pump is running at 3000 ± 200 rpm.

Although the Hannover technique is typically used for on-pump procedures, Cheung et al. successfully applied it without the use of a heart–lung machine (38). Additionally, the technique can be modified for LVAD explantation too (30). In accord with the idea of fully avoiding a sternotomy (34,35), Popov et al. applied a combination of bilateral anterior thoracotomies for HVAD implantation (39).

Redo sternotomy with a prior hemisternotomy also increases the risk of postoperative bleeding and infection, which, in some cases, can delay the timing of heart transplantation. Khalpey et al. have developed a robotic technique for LVAD implantation (r-VAD) that eliminates the need for a full sternotomy with a total endoscopic anastomosis of the aortic outflow graft (unpublished). Their experience in six patients has shown that r-VAD reduces cardiac bypass time and decreases bleeding and inflammation compared with the traditional approach. Continued investigation of these procedures, coupled with ideas to overcome inevitable barriers to changing an entrenched status quo, seem poised to influence the standard of care of these patients as new-generation pumps continue to get smaller.

Jarvik 2000 Heart

Building on an old surgical approach for pacemaker lead implantation, Frazier et al. at the Texas Heart Institute developed an extrathoracic, extraperitoneal, subcostal implantation technique for the Jarvik 2000 device (Jarvik Heart, Inc., New York, NY, USA) (41) (Fig. 2B). They initially used the technique in seven high-risk patients who had previously undergone cardiac surgery (including a sternotomy). First, the femoral artery and vein were exposed for cannula placement for cardiopulmonary bypass. A left-sided subcostal incision was made, and the rectus muscle was detached from connective tissue. By careful retraction of intra-abdominal organs, the peritoneum was kept intact. Subsequently, the diaphragm was incised in order to expose the left ventricle. The pump driveline was then tunneled to exit at the right costal margin.

Next, a suitable segment of the supraceliac aorta was exposed, and a prosthetic graft was sutured to the aorta as an extension of the outflow graft. Each of the seven patients underwent full heparinization and cannula placement for cardiopulmonary bypass. The diaphragmatic surface of the left ventricle was exposed, and the sewing ring was attached to it. The LVAD was prepared for insertion. To allow for air evacuation, the patient was placed in the Trendelenburg position. The ventricle was incised through the sewing ring, and an opening was made in the left ventricle with the Jarvik coring device for pump insertion. After the pump was properly placed, a graft-to-graft anastomosis was sometimes necessary to obtain optimal graft length. In general, Frazier et al. recommended joining the grafts directly from the pump to the aorta with minimal curving (41).

Synergy by CircuLite

The very small Synergy pump (CircuLite, Inc., Teaneck, NJ, USA) provides partial left ventricular support to nonterminal heart failure patients (42,43). Its implantation consists of two main steps: a right-sided mini-thoracotomy for inflow cannula placement and a subclavian incision for pump placement (Fig. 3B). First, the incision in the pectoral region is performed. The pump is then placed subcutaneously (similar to pacemaker implantation). The outflow graft is anastomosed to the subclavian artery. Next, the thoracotomy is performed. The pericardium is opened in order to access the target area in the convergence of both pulmonary veins into the left atrium. Then, the inflow cannula is placed into the left atrium and fixed. The inflow graft is tunneled through the second right intercostal space and connected to the Synergy device (44).

On-pump versus off-pump techniques

Independent of the specific LVAD chosen for implantation, patients in severe heart failure often tolerate cardiac manipulation or anesthesia poorly, so cardiopulmonary bypass may be necessary (38). Moreover, most LVAD implantations require partial or total cardiopulmonary bypass for left ventricular apex cannulation, given its technical aspects (45). On-pump techniques have important advantages for the surgeon, such as the increased ability to control hemodynamics, to inspect the left ventricle, and to perform concomitant procedures (24). Still, the use

of cardiopulmonary bypass can lengthen the operation and further compromise cardiac performance in patients with heart failure, especially with regard to the right ventricle.

In light of the above concerns, several reports have described successful off-pump techniques for the implantation, explantation, and exchange of different LVADs (34,38,41,46–50).

DISCUSSION AND CONCLUSIONS

The unexcelled long-term results of heart transplants—with survival rates now exceeding 50% at 15 years post-transplant—have made them the gold standard of treatment for patients with terminal heart failure (12). However, the continuously growing gap between the number of donor hearts and the number of candidates has led to an increased mortality rate on the waiting list. The few available donor hearts are being offered mostly to candidates in urgent need. Therefore, LVAD implantation has become a serious alternative for patients with terminal heart failure.

Currently, in patients receiving an LVAD as a bridge to transplant in a conventional operation that includes a full sternotomy and the use of cardiopulmonary bypass, the 6-month survival rate is more than 90%. That rate is comparable to that of heart transplant recipients (12). Nonetheless, some hurdles in LVAD surgery remain, such as bleeding, right ventricular failure, infections, and thrombus formation. The high hospitalization costs must also be addressed.

In view of those hurdles, minimally invasive LVAD surgery represents a recent, substantial paradigm shift. Conventional LVAD procedures have been associated with major incisions, high complication rates, and poor outcomes, but the advent of minimally invasive techniques is changing the entire field (25). With the fast development and miniaturization of next-generation devices, outcomes have improved significantly (24,33,51,52). Minimally invasive procedures mean smaller incisions, less blood loss, shorter hospital stays, and lower costs (5,6). Given the increasing number of LVAD implantations worldwide, we are convinced that the future of LVAD surgery is minimally invasive.

In contrast to other cardiothoracic procedures (such as coronary revascularizations or valve surgery), minimally invasive LVAD surgery is fairly new. No comparative studies showing medium-term or long-term results have been published. Yet most minimally invasive LVAD techniques have been adapted from other, already proven minimally invasive cardiac procedures (such as valve replacements or lung transplants).

Although the older LVAD implantation approaches involved extrathoracic incisions (34,53), the new techniques allow the pump to be inserted exclusively into the pericardium, avoiding a full sternotomy (24). As a result, only two thoracic regions must be accessed: the left ventricular apex and the ascending aorta. In all of the minimally invasive LVAD techniques described in the literature and in this review, those two thoracic regions are separated into isolated incisions and surgical tasks. Thus, two separate surgeons can simultaneously expose the apex and the aorta, thereby reducing the length of the operation.

To access the ascending aorta, the two minimally invasive surgical options differ substantially: a J-shaped upper hemisternotomy (24) or a right-sided parasternal thoracotomy (39). The thoracotomy fully avoids altering the sternum, but the hemisternotomy is well suited for redo LVAD implantations and concomitant procedures. With robotic LVAD implantations recently being developed (Khalpey et al., unpublished), the sternum could be entirely preserved in both patients with virgin chests and reoperation candidates with a left thoracotomy to place the LVAD and a total endoscopic anastomosis of the outflow graft on- or off-pump. Furthermore, the use of a robot (da Vinci Si System, Intuitive Surgical, Inc., Sunnyvale, CA, USA) adds dexterity and better 3D and high-definition vision, allowing even better placement of the outflow graft at the level of the diaphragm and up the right side of the heart, thus being safer before sternotomy for a heart transplant. Additionally, the robotic approach allows the option of using other graftable sites, such as the proximal subclavian artery, in reoperations if the aorta is not usable for the outflow graft. The surgeon should apply the option that best fits the individual patient's characteristics and that provides the greatest chance of an excellent outcome.

Another important factor to consider is the application of cardiopulmonary bypass. Off-pump LVAD implantation greatly shortens the surgical time. Also, the avoidance of cardiopulmonary bypass is known to decrease activation of the inflammatory and coagulation cascade, in turn decreasing the incidence of vasoplegia and coagulopathy (both of which often occur after LVAD implantation in these high-risk patients) (38). Thus, we believe that the combination of minimally invasive LVAD surgery with off-pump protocols should be the aim. Keep in mind, however, that the typical LVAD candidate with terminal heart failure might react negatively to even small cardiac

manipulations and be in great danger of decompensation. Although minimally invasive LVAD surgery is generating much well-deserved enthusiasm among surgeons, the need for caution cannot be overemphasized—particularly as comparative studies with medium-term and long-term results are still lacking. To ensure the highest quality of LVAD implantations, surgeons adopting minimally invasive techniques should already be very experienced in other types of cardiac surgery and must be diligent in evaluating their results.

Conflict of Interest: None of the authors has a financial relationship with a commercial entity that has an interest in the subject of the presented manuscript or other conflicts of interest to disclose.

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