Expert Consensus Paper: Lateral Thoracotomy for Centrifugal Ventricular Assist Device Implant

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Background. **The increasing prevalence of heart failure has led to the expanded use of left ventricle assist devices (VADs) for end-stage heart failure patients worldwide. Technological improvements witnessed the development of miniaturized VADs and their implantation through less traumatic non-full sternotomy approaches using a lateral thoracotomy (LT). Although adoption of the LT approach is steadily growing, a lack of consensus remains regarding patient selection, details of the surgical technique, and perioperative management. Furthermore, the current literature does not offer prospective randomized studies or evidence-based guidelines for LT-VAD implantation.**

Methods. **A worldwide group of LT-VAD experts was convened to discuss these key topics openly. After a PubMed search and review with all authors, a consensus was reached and an expert consensus paper on LT-VAD implantation was developed.**

Results. **This document aims to guide clinicians in the selection of patients suitable for LT approaches and preoperative optimization. Details of operative techniques are described, with an overview of hemisternotomy and bilateral thoracotomy approaches. A review of the best surgical practices for placement of the pump, inflow cannula, and outflow graft provides advice on the best surgical strategies to avoid device malpositioning while optimizing VAD function. Experts' opinions on cardiopulmonary bypass, postoperative management, and approaches for pump exchange and explant are presented. This review also emphasizes the critical need for multidisciplinary teams and specific training.**

Conclusions. **This expert consensus review provides a compact guide to LT for VAD implantation, from patient selection through intraoperative tips and postoperative management.**

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Heart failure (HF) is a growing global medical burden with a high impact on health care systems. It has been estimated that the prevalence of HF is approximately 1% to 3% of the adult population[1] and a further increase is expected owing to a higher proportion of elderly people and better survival of patients with cardiovascular diseases.[2] Nevertheless, availability of advanced end-stage HF therapies is compromised by the lack of heart donors, whereas the role of left ventricular (LV) assist devices (LVADs) has globally increased with improving results. Indeed, the Interagency Registry of Mechanically Assisted Circulatory Support (INTERMACS) annual report demonstrated 83% survival at 1 year, 73% at 2 years, and 46% at 5 years.[3,4] Technological advances have contributed to the growing success of LVAD therapies. Device miniaturization has allowed the development of less invasive surgical strategies[5] and more specifically, the lateral thoracotomy (LT) approach for LVAD implantation.[6]

The HeartWare HVAD System (Medtronic, Inc, Minneapolis, MN) is a centrifugal flow LVAD whose original clinical use was approved using the sternotomy approach.[7-11] Starting with the first less invasive HVAD implantations using the LT approach,[5,12] interest in this technique has steadily grown,[13-17] leading to the Conformité Européenne mark approval in 2016. Further clinical studies such as the LATERAL Clinical Trial[15] and approval by the US Food and Drug Administration of less invasive HVAD implantation followed in 2018. This new era of LT surgery is expected to improve outcomes of LVAD patients further by reducing critical perioperative complications such as bleeding and right heart failure.[12,15,16] The goal of this consensus article is to describe the best practices for preoperative, intraoperative, and postoperative management of patients undergoing LVAD implantations such as with an HVAD System, with an LT approach.

Nomenclature

To write any type of consensus paper, it is important to define the exact nomenclature. The worldwide first HVAD implantation through an LT approach was published under the definition of "upper hemisternotomy combined with anterolateral thoracotomy."[5] Another early description of the LT technique was presented with the name of "minimally invasive incisions."[12] Years later, the first HeartMate 3 (Abbott, Chicago, IL) implantation through LT was named "less invasive implantation."[18] Within the following years, based on several modifications[12,18] of the surgical technique,[5] many different terms were used worldwide (eg, sternum sparing technique, nonsternotomy, etc). This group of authors has decided that the LT approach for ventricular assist device implantation (LT-VAD) would be the most suitable description of this technique and therefore should be favored for increased homogeneity in describing LVAD implantations through LT.

Training and Education

Before starting an LT-VAD program, attention should be paid to the training process. Indeed, most clinical studies report data from specialized LVAD centers.[15] It is therefore essential to plan a training carefully for the whole interdisciplinary LT-VAD team, including surgeons, anesthesiologists, perfusionists, nurses, intensivists, and VAD coordinators.

The principles used in LT-VAD implants are common in other minimally invasive cardiac operations.[19] Access to the left ventricle (LV) for pump implant is similar to the approach for minimally invasive coronary artery or transapical transcatheter valve replacement surgeries. The approach for the outflow graft (OG) anastomosis is similar to techniques employed for minimally invasive aortic valve (AV) replacement. Therefore, skills acquired during these procedures will facilitate adoption of the LT-VAD approach.

Programmatically, the authors recommend a structured mentorship approach using LT-VAD expert proctors. Training programs should start with theoretical sessions and surgical hands-on courses. The subsequent phase of the LT-VAD educational program should focus on visiting highly specialized centers to observe LT-VAD procedures. This will allow surgeons to interact with an experienced LT-VAD team and receive insight into the management of LT-VAD patients. The third training phase should focus on one-to-one proctorship led by experienced LT-VAD surgeons.

Also critically important is ongoing, consistent education on procedural differences and expectations related to LT-VAD implantation. Moreover, the LT-VAD team should be tasked with internally evaluating outcomes.

Patient Selection

The patient selection process to choose the correct surgical technique is a key element that may influence postoperative outcomes. For HF patients, the main goal of clinical programs should be the maintenance of high standards and good results regardless of the surgical approach. Indeed, most patients can benefit from an LT-VAD approach. In particular, patients undergoing isolated LVAD implantation or in combination with AV surgery should be considered for LT-VAD without limitations related to the INTERMACS level.[17] Conversely, patients requiring concomitant surgery for tricuspid valve, multiple vessel coronary artery disease, left atrial clot removal, patent foramen ovale, or long-term right ventricle (RV) assist device (RVAD) should not primarily be considered for LT-VAD.

The complexity of patients chosen for LT-VAD implantation should be gradually increased after the completion of the training phase. It is advised to start an LT-VAD program with isolated LVAD implantations in patients without prior cardiac surgeries. This will facilitate the whole team in acquiring basic LT-VAD skills. Afterward, patients requiring LVAD implantation as a redo operation could also be considered for LT-VAD. This group of patients could potentially benefit most from LT-VAD in terms of surgical invasiveness, minimizing adhesiolysis and raw surface bleeding. When full

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experience with isolated LVAD implantation is acquired, combined procedures can be approached.

Preoperative Management

In all LVAD candidates, a careful presurgical evaluation is of highest importance to avoid unexpected events during the operation. In addition to the standard LVAD preoperative assessments, computed tomography (CT) and echocardiography assist in evaluating suitability for LT-VAD. A CT scan is advised to assess the position of the LV and identify the correct intercostal space for the LT-VAD incisions. The choice between an upper hemisternotomy and a right thoracotomy can be based on the size and position of the ascending aorta. A right anterior thoracotomy might be suitable when the aorta is to the right of the midline, whereas an upper hemisternotomy may be preferred when the aorta is in the midline or to the left. The main pulmonary artery may also be more accessible for temporary RV support through an upper hemisternotomy. Planning where to place the cannulation site, the partial clamp, or the OG based on CT scan images is essential in cases of calcifications or atherosclerosis. Furthermore, a CT scan is mandatory for redo cases and in planning OG tunneling. The position of the RV or open bypasses in relation to the sternum should be checked, and the way to expose the aorta without injuring open grafts should be planned.

Echocardiography is necessary to rule out concomitant valve diseases, to assess the patient's hemodynamic status and guide preoperative optimization. Evaluation of the LV and the left atrium for clots is recommended. If no thrombus and good flow in the left atrial appendage (LAA) are documented, the LAA closure may not be necessary in patients with sinus rhythm. In other cases, the use of a dedicated device for LAA closure should be planned. An intraoperative transthoracic echocardiogram should be performed to identify the intercostal space for the LT, usually corresponding to a mid to apical ventricular short-axis view. Accurate identification of the LV apex minimizes the length of the incision and helps guarantee an optimal surgical exposure.

Preoperative abdominal and pelvic CT scans are recommended to evaluate peripheral vasculature in preparation for cardiopulmonary bypass (CPB) cannulation, as well as to determine the percutaneous driveline exit site.

Hemisternotomy Approach

The first LT-VAD operation worldwide was performed combining an upper hemisternotomy with a left anterolateral thoracotomy.[5] In this technique, the patient is positioned supine and a 30-degree rotation to the right can be used for better exposure of the thoracotomy. The sterile field is prepared as for a full sternotomy. A *J*-shaped upper hemisternotomy is performed up to the second or third intercostal space (Figure 1A). The ascending aorta is exposed under the pericardium, which is fixated to the skin to facilitate exposure, and prepared for arterial cannulation. A left anterolateral thoracotomy follows with a 8- to 12-cm incision over the fourth or fifth intercostal space above the LV apex. The incision should be large enough to accommodate the pump itself; a slightly longer incision might be necessary in case of HeartMate 3 implantation owing to the larger size of this pump. The pericardium is locally opened and the LV is exposed. Typically, double-lumen intubation is not necessary because the pericardial stay sutures prevent the lungs from entering the surgical field. The correct spot for the LV core can be identified by gentle digital compression or insertion of a needle into the LV apex to identify the cardiac long axis toward the mitral valve (MV) under transesophageal echocardiogram (TEE) monitoring. The apical ring is then sewn to the heart using a standard partial muscle thickness technique. Several centers have transitioned to a few interrupted sutures followed by a running polypropylene suture because this technique provides excellent hemostasis. During this period, it is helpful to reduce the heart rate for easier stitch placement and occasionally administer lidocaine and magnesium to prevent ventricular arrhythmias. At this moment, the patient can be fully heparinized and CPB can be started using central (right atrium) or peripheral (femoral vein) venous cannulation with arterial cannulation through the ascending aorta or femoral artery. If the patient is unstable or sensitive to heart manipulation, CPB should be started in advance. The LV apex is then cored (Figure 1B), allowing inspection and removal of thrombus or loose materials (eg, trabeculae) that could occlude the pump. The LVAD pump can now be fully inserted into the LV apex. Fixation by the sewing ring is carried out after proper direction of the OG is ascertained. Depending on the implanted device, pump fixation to the sewing ring implies different handling of the pump. The inner portion of the HVAD sewing ring contains a C-clamp that can be adjusted through a single screw. To fasten the apical ring to the pump easily, longer, slim, or angled instruments and screwdrivers for LT approach have been designed to address the deeper and limited working area at the thoracotomy site. Furthermore, the surgeon should consider sewing the apical ring with the tip of the screw toward the sternum to insert the screwdriver from the ventral part of the incision later and vertically reach the screw (Figure 1B). Contrary to HVAD, the HeartMate 3 inflow cannula is inserted into the apex through a slide lock system that anchors it to the apical cuff without using an additional tool. Because of the depth of the surgical field, it might be difficult to reach the locking system directly with hands; a surgical clamp could be helpful to grab and control the slide lock system.

During insertion of the LVAD, it is important to keep the OG unclamped and connected to pump suction so as not to entrap air in the ventricle and allow LVAD deairing. The OG is then tunneled from the thoracotomy to the upper hemisternotomy, through the pericardium along the diaphragm and around the right atrium, so as not to be in the field for future sternotomy or impinge on the RV.

Before performing the OG anastomosis, the driveline exit should be prepared[20] on the side previously discussed with the patient and according to preferences,

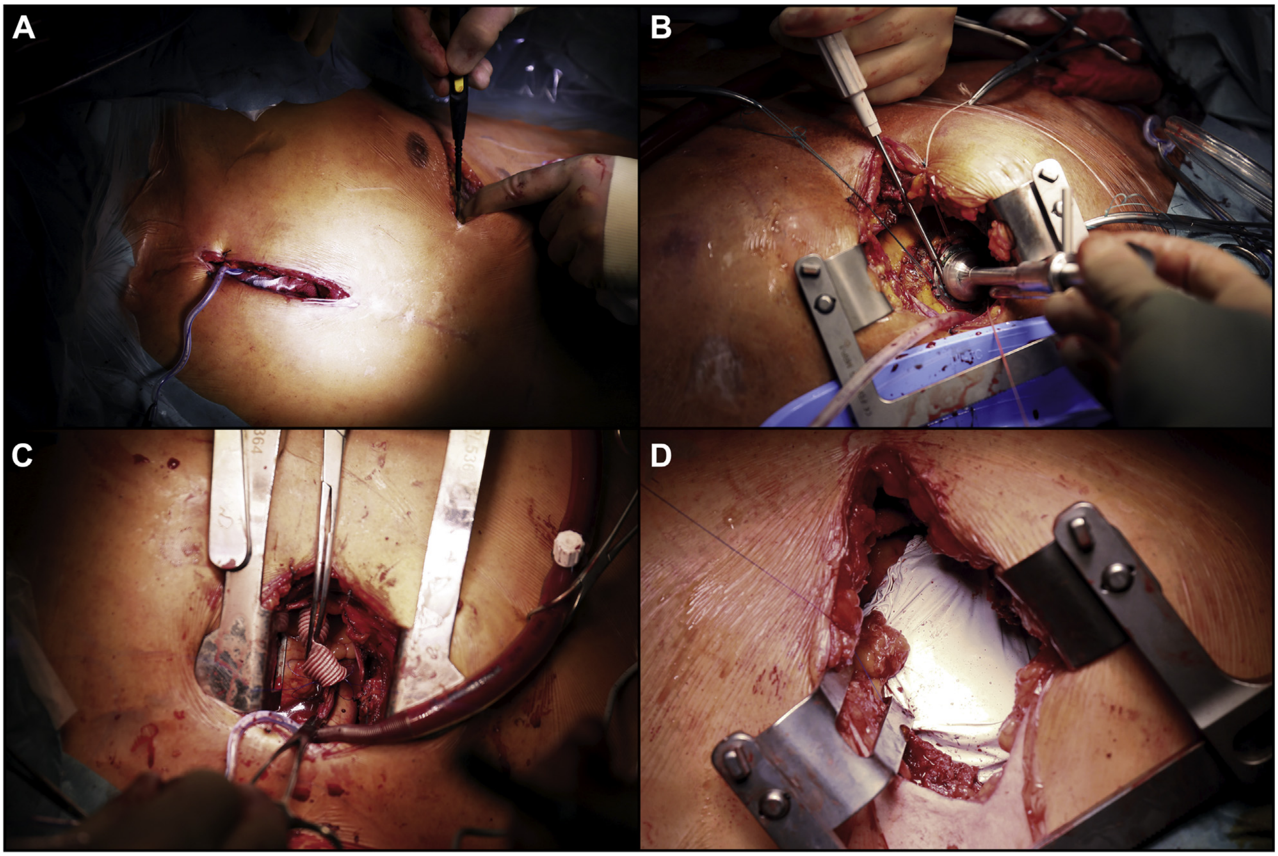


Figure 1. Intraoperative view of left ventricular assist device implantation through lateral thoracotomy approach. (A) Surgical incisions located on the upper part of the sternum and at the fourth or fifth intercostal space. (B) Implantation of the apical ring through left thoracotomy and preparation for the left ventricular core. A dedicated screwdriver is already prepared in place for the subsequent pump fixation to the apical cuff. (C) Outflow graft anastomosis on the ascending aorta. (D) Positioning of a patch to cover the pump before chest closure.

sleeping habits, and previous abdominal operations. In the conventional technique, an incision is made at the right or left border of the rectus abdominis muscle, 2 cm below the costal margin. The fascia is incised, and the driveline is directly tunneled through the muscle and above the posterior fascia. Alternatively, a double tunnel driveline technique includes placing the driveline in the sheath of the rectus muscle with a 2-step procedure.[20] At first, the driveline is tunneled toward the umbilical direction through a small incision on the medial line, and then subcutaneously to the left or right upper quadrant.[20] Before implantation, the driveline itself can be wiped with an antibiotic moistened lap sponge. The final intrathoracic position of the driveline should be verified to avoid sharp curves and kinking that can damage the electrical wires over time.

Deairing can be started at this stage in a retrograde fashion, filling the heart and the pump, and clamping the OG. The OG is then anastomosed end-to-side to the ascending aorta (Figure 1C). Final deairing can be performed before tying the OG anastomosis, by reducing CPB and running the pump at low speed with the partial clamp. Gradual weaning from CPB and pump speed adjustment is then performed. The pericardium above the aorta may be partially closed directly or through the use of a membrane. Placement of a patch is suggested (eg, GORE-TEX Cardiovascular Patch, WL Gore & Associates, Inc, Flagstaff, AZ; bovine pericardium or extracellular matrix) between the pump housing and the chest wall to avoid direct mechanical contact of the pump with the parietal pleura, the lung, and the phrenic nerve, and minimize postsurgical pain, adhesions to the lung, erosion of the chest wall, and bleeding[20,21] (Figure 1D). Similarly, the exposed part of the OG can be wrapped in a patch to avoid damage during reoperations. The use of a patch covering the pump and the OG is particularly relevant in bridge-to-transplantation patients because this technique will facilitate surgical preparation before transplantation, reducing the risk for major blood loss and damage to vital structures.

The main advantage of the hemisternotomy approach is the safe access to the aorta, which allows quick CPB cannulation and easy placement of the clamp. Moreover, exposure of the aorta allows the surgeon to complete operations on the AV and ascending aorta. In redo cases with open bypass grafts, the hemisternotomy permits safe isolation of the proximal venous and arterial grafts without exposing the ventricles to extensive dissection. An inverted *T* ministernotomy may also facilitate easier visualization during redo cases. In case of primary implants, the main body of the sternum remains intact, preventing bleeding and adhesions of mediastinal tissues while preserving the mechanical dynamics of the thoracic wall. This will help in a quick recovery and with future reoperations.

Bilateral Thoracotomy Approach

Since the early descriptions of the LT-VAD technique,[5,12,18] several modifications were developed (eg, a combination of bilateral anterior thoracotomies[13,14]) (Figure 2). In this approach, the left anterolateral thoracotomy is used to place the LVAD pump, but a right anterior minithoracotomy through the second or third intercostal space is used to position the OG. The 4- to 5-cm right anterior mini-thoracotomy is performed close to the sternal margin. The internal thoracic artery is divided; if needed, the second or third rib might be dislocated to enhance exposure.[13,14] Pericardial mobilization and retraction are critically important. Single-lung ventilation is usually not necessary because the pericardial retraction sutures isolate the operative field. Central cannulation using TEE guidance is possible and preferred because this practice pulls the heart toward the right chest, facilitating OG placement.

Although the approach to the aorta may be more challenging, this full sternal-sparing approach may reduce the surgical risk for a redo sternotomy in subsequent operations and allows for a less extensive mediastinal dissection.[14] However, this procedure has a learning curve that should not be underestimated. Concomitant procedures during a bilateral thoracotomy LVAD implantation are possible, such as AV surgery. Through the ventricular apex, it is possible to perform an edge-to-edge repair of the MV, as well as an AV closure, depending on the experience of the center. However, with increased surgical complexity, the authors still recommend a conventional sternotomy approach.

Inflow Cannula and Pump Position

Implantation of the inflow cannula at different angles with respect to the apical ventricular axis is a key step in LVAD surgery, which influences device performance, LVAD thrombosis, suction events, and patient outcomes. Computational fluid dynamics studies demonstrated that inflow cannula angulation greater than 7 degrees from the LV apical axis is associated with distorted hemodynamics.[22] A preoperative evaluation with CT scan and echocardiography can display the angulation and rotation of the heart, the direction of the MV in relation to the apex, and the position of the RV and interventricular septum.[23] This becomes particularly useful in patients with challenging anatomical features, morbid obesity or malnutrition, prior cardiac surgery, or chest radiation. In case of ischemic cardiomyopathy, an electrophysiologist should be involved to locate scars that can trigger ventricular tachycardia after placement of the LVAD pump. Such preoperative planning helps identify the ideal location for the thoracotomy incision so that the surgical field exposes the LV in the direction of the apical axis, facilitating optimal positioning of the inflow cannula. Furthermore, with the thoracotomy approach, the heart remains in the natural position, allowing the surgeon to predict the final orientation of the inflow cannula. After correct identification of the pump position, the sewing ring should be sutured close to the left anterior descending artery and about 1 cm anterior to the apex, in an anterolateral position, or alternatively at the LV apex dimple. At the end of the operation, the surgeon should confirm that no tractions or compressions are applied to the pump, to avoid postoperative bleeding, arrhythmias, and malpositioning. Final intraoperative TEE imaging should be performed to confirm optimal inflow cannula orientation before the operation room is left.

Outflow Graft

Positioning of the OG has a key role in patients' long-term outcome. Suboptimal positioning may lead to turbulence in blood flow, resulting in a high risk for thrombosis, twisting, or kinking.[24-26] Indeed, shallower angles of the outflow-aortic anastomosis (45 to 60 degrees) result in favorable hemodynamics compared with the 90 degrees configuration, which is the most thrombogenic.[24] Conversely, a bigger outflow-aorta angle can increase recirculation owing to aortic regurgitation.[26]

After pump placement, the OG may be tunneled intrapericardially, or in redo cases, through the left pleural space under direct vision or thoracoscopic guidance. In case of previous bypass surgery, the OG can be tunneled safely above left mammary artery grafts, but a course to the right pleural cavity may also be suitable. The OG should not be positioned below the sternum or impinging on the RV. Tunneling of the OG through the transverse sinus is also possible and guarantees protection of the OG in future operations.[27] In case of a severely diseased aorta, surgeons can consider alternative target vessels such as the brachiocephalic artery[28] exposed through an upper hemisternotomy, the left or right subclavian artery[29,30] exposed through a local incision, or the descending aorta exposed through an extended left thoracotomy[31] (Figure 3).

After tunneling, the OG should be filled to size its length properly and should be checked for twisting, kinking, and obstructions. The OG anastomosis should be performed using a partial occluding clamp positioned slightly toward the side aspect of the aorta. This guarantees a lateral course of the OG to avoid adhesions to the sternum. Elements of the bend relief can be removed before pump implantation to avoid compression by the chest wall, which could change the orientation of the pump housing and direction of the inflow. The bend relief can also have considerable tissue ingrowth over time, making mobilization during transplant challenging. Hence, some surgeons envelop the bend relief in a pericardial membrane.

On-Pump and Off-Pump LVAD Implantation

Cardiopulmonary bypass support is typically used at the time of LVAD implantation through central or peripheral

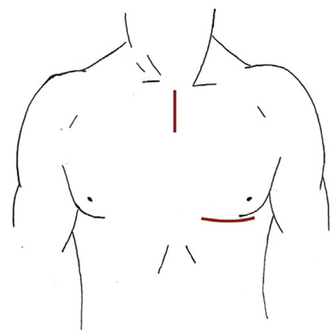
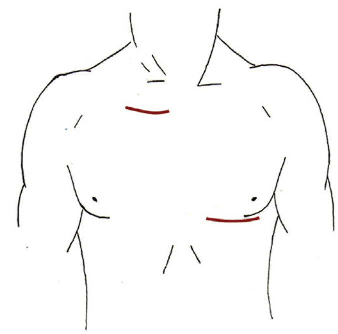
	Hemisternotomy	**Bilateral Thoracotomy**
		
Pump positioning	Left anterolateral thoracotomy	Left anterolateral thoracotomy
Outflow graft	Upper hemisternotomy (up to 2nd-3rd intercostal space)	Right anterior thoracotomy (2nd- 3rd intercostal space)
Arterial cannulation	Ascending aorta, femoral artery	Ascending aorta, femoral artery
Venous cannulation	Femoral vein, right atrium	Femoral vein
Advantages	Direct aortic cannulation, easier outflow graft anastomosis, concomitant procedures possible	Intact sternum, less adhesions in reoperation, concomitant procedures possible
Disadvantages	Partial opening of the sternum	Not suitable for all patients (preoperative CT scan for position of the aorta), could be technically more challenging, pain

Figure 2. Differences between the hemisternotomy approach and the bilateral thoracotomy approach. (CT, computed tomography.)

cannulation. In addition, it might be helpful to place a vent in the ascending aorta for deairing during CPB weaning. Placing the patient on CPB during LT-VAD implantation has several advantages. Manipulation of the heart under CPB avoids hemodynamic instability and possible complications are easier to manage. The heart is unloaded during pump insertion and resection of trabeculae, thrombus removal, or other concomitant procedures can be safely performed. Moreover, CPB is recommended in redo cases.[32] In some centers, the use of CPB is limited to coring and insertion of the pump only, reducing CPB times to less than 10 minutes.

Nevertheless, an alternative off-pump approach has been developed.[33] At these times, only a few authors

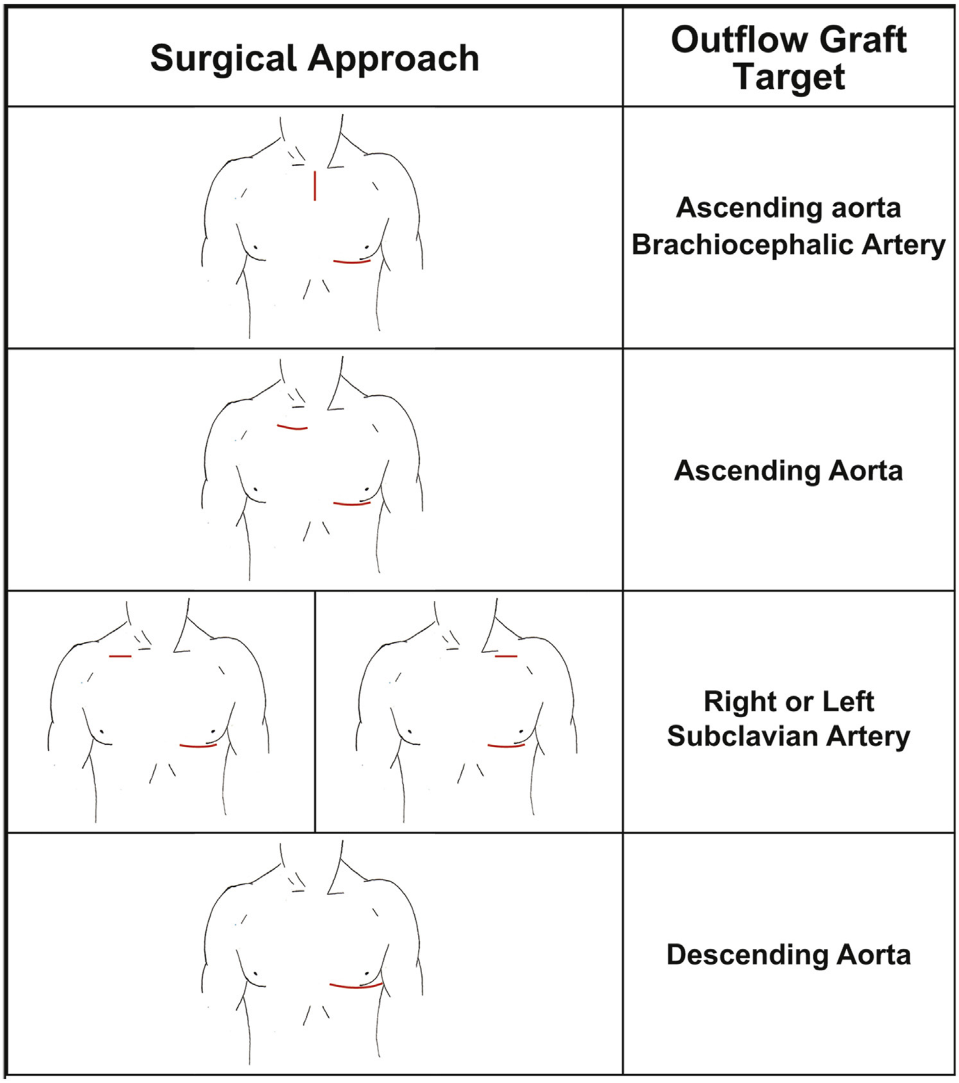


Figure 3. Lateral thoracotomy left ventricular assist device surgical options for different potential outflow graft anastomosis strategies.

apply routinely off-pump LVAD implantation to reduce hemodilution, systemic inflammatory response, negative effects of pulmonary hypertension, and postoperative RV dysfunction.[30,34,35] However, these advantages are overruled by higher intraoperative safety using CPB. Although off-pump LT-VAD may be considered an alternative strategy in patients with a contraindication to aggressive anticoagulation,[34] special care should be taken during the apical coring procedure. The coring knife can be introduced with minimal blood loss, but after its removal, a considerable amount of blood can be lost until the pump is introduced into the LV cavity; hence, the LVAD should be promptly inserted without the chance to inspect the LV cavity. To mitigate this blood loss, adenosine can be administered, or a short phase of induced ventricular tachycardia or rapid pacing may be helpful. Owing to the lack of direct visualization of the LV, extreme care must be given to rule out thrombus within the LV using TEE.

Cardiopulmonary bypass is recommended as the reference standard in LT-VAD because it guarantees a safe approach through stable hemodynamics, reduced blood loss during the coring process, direct retransfusion of pericardial blood, and RV support. When an off-pump approach is preferred, preparation for fast initiation of CPB is recommended in case complications occur.

Right Ventricular Failure

Right ventricular failure has been described as one of the most dreaded complications after LVAD implantation owing to intraoperative manipulation of the heart, postoperative leftward shift of the interventricular septum, and hemodynamic changes in the cardiac output. Severe RV failure requiring RVAD support is associated with a reduced survival.[3] One of the main benefits of LT-VAD implantation is preservation of the RV geometry during surgery. With conventional sternotomy, the ventral part of the pericardium is opened, the right atrium is cannulated, and the heart is luxated, leading to a modification of RV shape and volumes.

In contrast, during LT-VAD, the pericardium remains mainly closed, leading to further stabilization of RV function and avoiding RV dilation during LVAD startup.[5] The protective role of LT-VAD is confirmed by the low incidence of postoperative RV failure and reduced need for RVADs,[15,36] which are required in 0.7% to 6.1% of cases.[15,17,36]

Patient selection and preoperative optimization have an important role in preventing RV failure. Medical treatment should be enhanced with adequate administration of diuretics and inotropes, guided by continuous invasive hemodynamic monitoring to identify the best timing for LVAD implantation. When RV support is needed, it can be achieved through cannulation of the pulmonary artery and femoral vein, or with femorofemoral venoarterial extracorporeal membrane oxygenation. Alternatives for RV support may include devices such as Impella RP (Abiomed, Inc, Danvers, MA). New double-lumen cannulae, such as those used with the ProtekDuo TandemHeart Pump (LivaNova PLC, London, UK), are characterized by a percutaneous insertion through the internal jugular vein, with the proximal inflow lumen in the right atrium and the distal outflow lumen in the main pulmonary artery. In both cases, device positioning requires the use of fluoroscopy. Therefore, the authors advise establishing a strategy for RVAD implantation before starting the operation, including the potential use of a hybrid operating room when a percutaneous RVAD is expected.

Postoperative Management

The benefits of LT-VAD techniques are clear soon after surgery and persist into the medium term. Several single-center and multicenter studies documented improved outcomes with 92.4% 6-month survival, 87% 2-year survival, and 98% 1-year freedom from disabling stroke.[15] Favorable outcomes have also been demonstrated in INTERMACS-1 patients with a higher 30-day and 1-year survival rate compared with conventional sternotomy.[17] In addition, LT-VAD is associated with a shorter hospital stay, which varies on average between 6 and 23 days, depending on the preoperative conditions.[15,17,28,37]

Main advantages of LT-VAD are the reduced transfusion need[27] and a low rate of reoperations for bleeding.[15,17] Minimization of bleeding allows for early anticoagulation and the prevention of pump thrombosis, whereas the low transfusion rate may decrease systemic inflammation and sensitization. Reduced bleeding also helps to stabilize the blood pressure, which should target a mean value of 80 mm Hg to prevent total unloading of the LV and leftward shift of the septum. Optimizing LV unloading avoids changes in RV geometry, contributing to RV stability. Moreover, with this level of afterload, the LVAD pump can run at manufacturer-recommended speeds with reduced risk for suction events. The reduced need for transfusions and a stable intravascular volume lead to an optimal central venous pressure (<12 mm Hg), which prevents RV distention, liver congestion, and renal complications. These factors contribute to a quick hemodynamic stabilization after surgery, rapid extubation, and early anticoagulation (starting heparin 6-12 hours after implant and oral anticoagulation on postoperative day 1). Ultimately, the postoperative management of an LT-VAD patient should aim for a hospital discharge within 14 days from surgery, after optimization of patient's general status.[37]

To achieve such a goal, it is important to enhance pain control, physiotherapy, and patient training. Local anesthetic or intercostal nerve block can be used to control pain in the first hours after the operation, and analgesic therapies combined with antiemetic drugs should be used in the following days to facilitate patient mobilization. Although data on intraoperative intercostal nerve cryoablation[38,39] during LVAD implantation are lacking, it has been demonstrated that optimizing analgesia using a regional nerve block is associated with reduced opioid use and less postoperative pain after LVAD implantation through LT.[40] Accordingly, a left serratus anterior nerve block at the site of LT incision and a right anterior intercostal nerve block at the site of right thoracotomy should be considered in the context of a multimodal analgesic approach.[40] Contrarily, paraspinal blocks such as epidurals are contraindicated to allow early anticoagulation.

Ventricle Assist Device Exchanges and Pump Explant

Despite improvements in LVAD outcomes, several complications might require pump replacement. Pump thrombosis affects nearly 10% of all LVAD recipients, regardless of device type.[41,42] Although the best treatment for pump thrombosis remains to be delineated, the authors suggest an early pump exchange unless the patient presents with severe end-organ dysfunction and extremely high mortality risk. If infection or OG obstruction is diagnosed, LVAD exchange is typically performed through full sternotomy to allow removal of the entire LVAD, driveline, and OG. If isolated LVAD thrombosis is confirmed, a pump exchange through LT can be performed safely. A 15- to 20-cm LT incision is made directly over the pump. It may be helpful to notch or resect a rib to prevent postoperative crepitus and gain optimal surgical access. Dissection should be carried out to expose the pump body, apical ring, and driveline. At least 5 cm of OG should be exposed to allow for removal of the bend-relief rings and for hemostatic control. Once dissection is completed, CPB can be started through the femoral vessels. The LVAD is turned off and the OG is clamped. The driveline is divided distally. If graft-to-graft anastomosis is planned, the clamped OG is divided. If direct connection of the old OG to the new pump is planned, the pump is disconnected from the graft and the bend-relief. The connection on the sewing ring is loosened and the pump is removed. Because of epithelization and adhesion, often a twisting motion is required to

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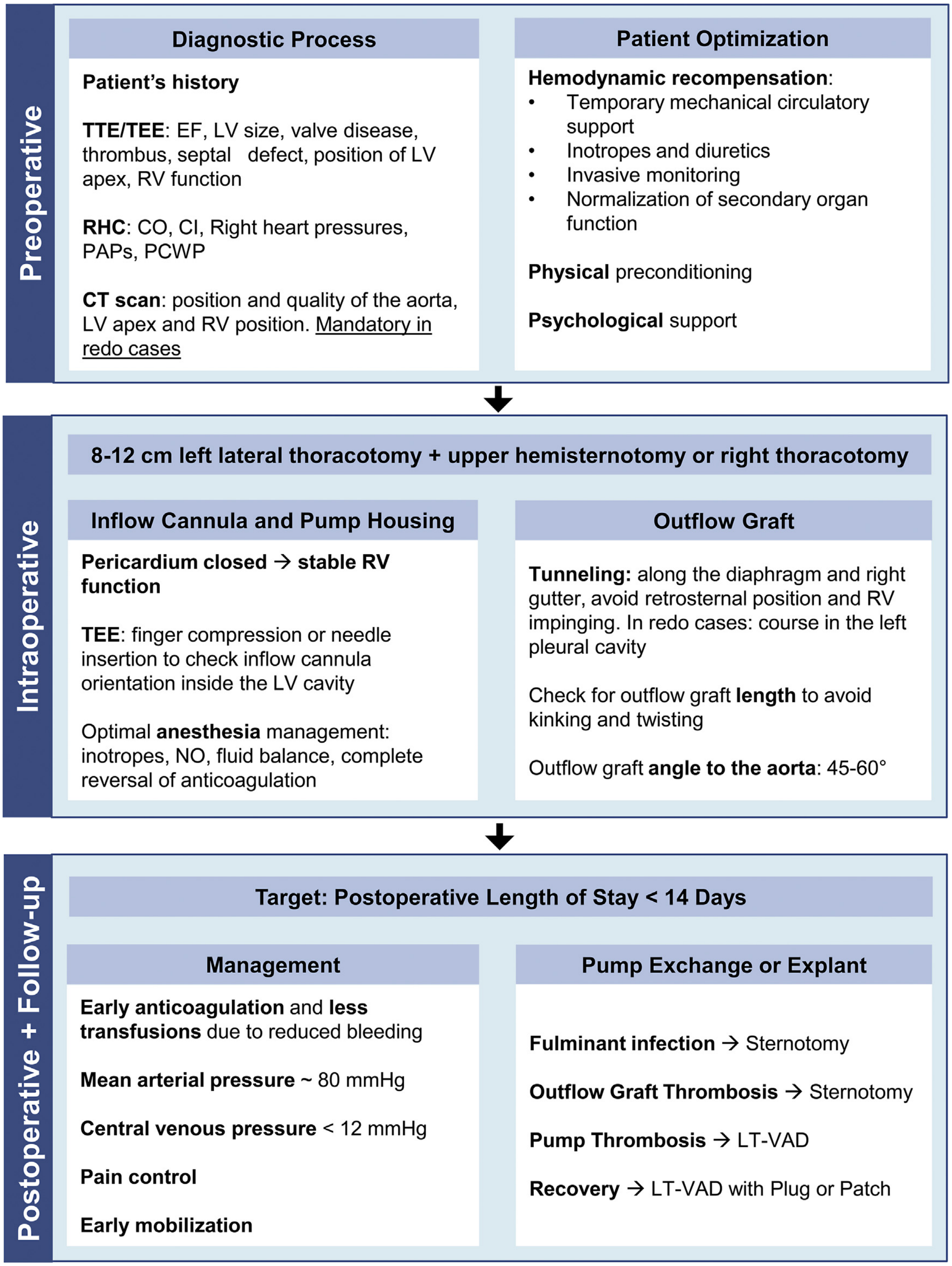

Figure 4. Workflow for left ventricular assist device implantation through lateral thoracotomy. CI, cardiac index; CO, cardiac output; CT, computed tomography; EF, ejection fraction; LT-VAD, lateral thoracotomy left ventricular assist device; LV, left ventricle; NO, nitric oxide; PAPs, pulmonary artery pressures; PCWP, pulmonary capillary wedge pressure; RHC, right heart catheterization; RV, right ventricle; RVAD, right ventricular assist device; TEE, transesophageal echocardiogram; TTE, transthoracic echocardiogram; VAD, ventricular assist device.)

remove the LVAD. The edges of the ventriculotomy are debrided. The ventricle is allowed to fill as the new pump is inserted and secured. The graft-to-graft anastomosis or the direct connection of the old OG to the new pump is then performed. Deairing can be safely achieved using a 20-gauge needle on the OG proximal to the clamp while running the LVAD at a low speed with the heart progressively filled. Trendelenburg and carbon dioxide should be used.

In a few cases, a pump explant after LV recovery is indicated. The general LT surgical approach for LVAD explant is similar to LVAD exchange. Several explantation strategies have been described in the literature. These include ventriculoplasty with removal of the sewing ring or sewing ring preservation and occlusion of the ventriculotomy.[41,42] Unless explanting for infection, it is preferred only to explant the pump and ligate the OG, while leaving the sewing ring in place. This approach allows for a limited dissection, ease of reimplantation in case of need, and an intact LV geometry. Several custom-manufactured plugs have been reported to close the ventriculotomy under compassionate use conditions.[43] It is also possible to close the ventriculotomy with a patch (ie, with bovine pericardium, GORE-TEX Cardiovascular Patch, and extracellular matrix). The patch is tailored to be the size of the sewing ring and is parachuted into the ventricle after placement of mattressed 4-0 polypropylene sutures with knots on the epicardial side. An additional patch is then sutured over the ring to ensure hemostasis. There are successful case reports in which the pump was simply stopped and left in place after the driveline was shortened below the skin level, but there is not enough evidence to advocate for this approach or for surgical removal of the device.

Future Directions and Conclusion

Since the first successful LVAD implantations, the technological and surgical progresses have led to wide LVAD use with improved outcomes and good patient quality of life.[2,3] As the miniaturization process of LVADs continues, the application of less invasive implantation techniques is likely to increase. Indeed, less invasive approaches enable LVAD implantation to be performed with results equivalent to or better than those of conventional techniques when in expert hands. The literature supports such clinical trends with a few observational studies[36,37] and the multicenter, prospective, noninferiority LATERAL Clinical Trial.[15] More large studies are warranted to provide the compelling evidence for the efficacy of LT-VAD. Further delineation of the ideal patient profile that could benefit from LT-VAD will facilitate clinical decision-making. Better insight into RV physiology during LT-VAD surgery is also required to optimize outcomes, especially in the case of preexisting RV impairment. Moreover, LT-VAD techniques may be a paradigm for the future in terms of cost-effectiveness. A comparison between Medicare data for LVAD implantation and costs derived from the LATERAL Clinical Trial[15] demonstrated that mean total index hospitalization costs for thoracotomy were 21.6% lower compared with conventional sternotomy.[44] If the same quality of operation can be performed through a less traumatic incision, resulting in a shorter hospital stay and lower overall costs, this approach would coincide with the goals of managed care.[44] With the growing number of LT-VAD implants, future device designs may be considering this approach , potentially allowing for even simpler surgical implant techniques.[6]

This review provides a comprehensive consensus on the best practices for preoperative, intraoperative, and postoperative management of patients undergoing LT-VAD implantation such as with an HVAD System (Figure 4). Continuous monitoring of patients' outcomes should aim to improve clinical practice, and caution should be emphasized because conventional LVAD implantation techniques remain our measure for comparison. However, we suggest that all centers and surgeons approaching the LT-VAD technique adhere to this consensus on the best practices and consider the importance of the guidance of experienced teams.

REVIEW

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