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REVIEW ARTICLE

Left ventricular assist device exchange: a review of indications, operative procedure, and outcomes

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Abstract
The use of left ventricular assist devices (LVADs) is intended to treat patients with end-stage heart failure. Owing to technological advances, these devices are becoming more durable. However, LVADs may need to be exchanged when complications arise and heart transplantation is not possible. Indications for LVAD exchange (LVADE) include device thrombosis, device infections, and pump component failure. LVADE has historically been associated with a high risk of morbidity and mortality. In this review, we discuss the indications of LVADE, the decisional and technical aspects during surgery, and outcomes.

Keywords Exchange · Replacement · Heart failure · Left ventricular assist device · LVAD · Driveline infection · Pump thrombosis · Pump failure

Introduction

Left ventricular assist device (LVAD) implantation is progressively becoming a viable solution to treat heart failure and promote myocardial remodeling [1]. According to the Society of Thoracic Surgeons (STS)-Interagency Registry for Mechanically Assisted Circulatory Support (INTERMACS), 78.1% of patients receive an LVAD as destination therapy, 15.2% as bridge-to-candidacy (BTC), and 6.6% as bridge-to-transplant (BTT). At long-term follow-up, 44.2% of patients are alive on device 5 years following first LVAD implantation [2]. The increasing durability of current generation LVADs, together with an overall higher patient risk profile, highlights the importance of managing specific complications related to these devices [3]. Most commonly reported major adverse events after LVAD implantation include bleeding requiring surgery, gastrointestinal bleeding (GIB), neurological events, pump thrombosis, blood trauma due to excessive forces generated by the mechanical pump, device failure, infections, and right ventricular failure [4, 5]. LVAD exchange (LVADE) represents one of the possible therapeutic strategies for some of these complications. Historical data regarding LVADE reported in 2004 from the REMATCH trial included 29 LVADE in 23 patients (accounting for 33.8% of total LVAD recipients). The study compared the outcomes of patients affected by advanced heart failure treated with optimal medical therapy alone or LVAD implantation with the HeartMate-VE (HM-VE). All LVADE were performed with another HM-VE. The 1-year freedom and 2-year freedom from device replacement were 87% and 37%, respectively [6, 7]. Subsequently, multiple studies have compared results of LVADE in specific settings and defined the impact of improving technologies. The MOMENTUM 3 trial demonstrated a significantly lower 2-year LVADE rate after implantation with the HeartMate 3 (HM3, Abbott, Abbott Park, IL) when compared to the HeartMate 2 (HM2) (2.3% vs. 11.3%, respectively [$p < 0.001$]) [8]. These data are comparable with other published works [9, 10]. In this review, we discuss the therapeutic strategies when dealing with the indications of contemporary LVADE, decisional and technical aspects, and outcomes.

Main indications for device exchange

The specific indication for LVADE strongly impacts outcomes (Table 1). Depending on which LVAD generation is considered, the main indication for pump exchange is

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generally device thrombosis, which represents about 2/3 of all procedures [6, 11, 12]. A recent systematic review reported an incidence of device thrombosis between 2 and 11% of all LVAD recipients (less than 0.04 events per patient-year) [13]. Surgical treatment of this complication may be required because of unsatisfactory outcomes and high mortality reported in patients managed conservatively [14]. This is particularly important as increases in prophylactic antithrombotic therapy to mitigate thrombosis have been associated with a higher incidence of hemorrhagic cerebrovascular events and death [15]. A recent systematic review and meta-analysis showed that surgical pump exchange is superior to medical therapy with a higher success rate of pump thrombosis resolution (81.3% vs. 45.4%; $p < 0.001$), lower mortality rate (16.7% vs. 34.5%; $p = 0.013$), and lower recurrence rate (11.8% vs. 38.3%; $p < 0.001$) [16].

Regarding infection with need for LVADE, these patients tend to have worse outcomes than those surgically treated for device malfunction or thrombus [19]. Device infection represents 12–18% of LVADE indications and includes driveline infection (5 to 44% of patients), pump pocket infection (0 to 22% of patients), and refractory sepsis (0 to 33% patients) [13, 20]. It is difficult to define the best treatment strategy in cases of device infection because of the heterogeneity of this scenario (i.e., specific causative microorganism, portion of device affected, clinical context). The specific indications for LVADE in this context have yet to be defined. Nevertheless, a recent systematic review and meta-analysis demonstrated LVADE does not appear to confer an advantage as compared to conservative strategies. There were no significant differences in the overall mortality (exchange 17.6% (4.3–50.6) vs. non-exchange 23.3% (15.8–32.9), $p = 0.67$) and infection recurrence rates (exchange 26.7% (8.7–58.0) vs. non-exchange 38.6% (15.4–68.5), $p = 0.56$) [21]. Regardless, it remains important to clarify the role of technical aspects that can influence surgical outcome in device infection. These include surgical technique, grade of debridement, necessity for omentum wrapping, use of antibiotic-impregnated cement and implants, antimicrobial washout solutions, and duration of antibiotic therapy [22]. It has been also demonstrated that patients who underwent exchange after more than 150 days of active infection had worse outcomes than those who underwent exchange earlier [19].

Another non-infrequent indication for exchange is failure of LVAD components other than the pump (e.g., pump controller, battery, and monitor). This complication has been dramatically reduced by technological advancements, with more reliable devices in third-generation LVADs. Only 13 to 15% of device malfunctions are due to pump failure. However, failure of the integrated driveline can necessitate external repair but also LVADE if the

Table 1 Summary of indications, definitions, and outcomes for left ventricular assist device exchange [17]

Indications for LVADE	Definition	Outcomes
Device or component failure/malfunction (levitation error, tear of inflow cannula, technical failure, driveline defects)	A device malfunction occurs when any component of the system ceases to operate to its designed performance specifications or otherwise fails to perform as intended	Treatment decision strongly related to specific device malfunction. Limited data about the outcomes [12]
Pump thrombosis	Confirmed thrombus within the blood-contacting surfaces of device inflow cannula or outflow conduit or grafts	LVADE reported in 37% of patients. Surgical pump exchange is superior to medical therapy with a higher success rate of pump thrombosis resolution, lower mortality rate, and lower recurrence rate [14]
Device infection	Refractory infection of external surfaces (e.g., progressive local or systemic complications despite antimicrobial therapy), severe infections of the internal surfaces of the VAD (e.g., pump/cannula infections or VAD endocarditis) [18]	LVADE reported in 11% of patients [15], limited and contrasting data about the outcomes [15, 16]
Driveline damage	Mechanical injury to the driveline at both internal and external locations, electrical malfunction, and cable damage	LVADE reported in 49% of patients, particularly with internal damage [5]

involved portion of the driveline is too close to the skin exit site or at its junction with the LVAD [23].

Timing of LVAD exchange

In the majority of cases, LVADE must be done urgently while managing the patient with medical therapy in the interim. For most cases of device thrombosis, the patient retains partial LVAD output until the device is substituted [19]. Comorbid conditions must be optimized before LVADE to mitigate complications frequently associated with LVADE. Preoperative considerations and studies before LVADE are fundamental to successful outcome that have been reported by Adamson and colleagues [24]. In general, these steps include accurate diagnosis of LVAD failure, assessment of infection (fluorodeoxyglucose (FDG)-positron emission tomography (PET)/computerized tomography (CT) scan [25]), determination of native cardiac function and presence of valvular disease (e.g., echocardiogram, pulmonary artery catheterization), assessment of chest anatomy and presence of existing adhesions (e.g., chest CT scan), choice of a replacement LVAD, and consideration of a new driveline exit site [26].

From a clinical point of view, the preoperative steps to be considered are medical stabilization of the patient (e.g., vasopressors or inotropes and antibiotics if necessary), need for anticoagulation therapy, discontinuation of long-acting anticoagulant and antiplatelet therapy, and use of continuous heparin infusion, when necessary. According to a recent expert review, preoperative medical management should be targeted to the most dangerous complications of LVADE: discontinuation of long-acting agents that may suppress the sympathetic nervous system against the risk of vasoplegia (e.g., beta-blockers, angiotensin receptor blockers, neprilysin inhibitor/angiotensin-converting enzyme inhibitor); optimization of right ventricular function with inotropes, diuretics, or temporary mechanical support in the event of right heart failure; and optimization of coagulative function to mitigate bleeding risk [27]. The importance of CT scan with three-dimensional (3D) reconstruction during preoperative planning has also been highlighted in cases of LVADE for determining the optimal route of surgical access [27].

Technical aspects of LVAD exchange

The surgical approach to device exchange may vary. Specific surgical strategies for LVADE have been previously described [3, 28]. Table 2 summarizes the main factors determining surgical approach for LVADE.

Surgical access can range from traditional full-sternotomy or redo-sternotomy to an alternative minimally invasive technique. Novel surgical approaches have been developed to minimize complications related to re-do surgery in cases of LVADE. These are helpful in reducing surgical trauma, risk of blood loss, arrhythmic complications, and in decreasing intensive care unit and overall in-hospital length of stay. Additionally, the risk of right-sided heart failure can be reduced with less invasive techniques as the right ventricle remains in its natural position [3]. Implantation with less invasive techniques is becoming the gold standard due to these potential benefits combined with the non-inferiority of their surgical outcomes.

It is important to define the extent of the dysfunction affecting the device as it may be necessary to change only a portion of its components. The traditional approach through redo-sternotomy (as sternotomy is currently the most common access used during the first implantation) implies greater complexity due to presence of adhesions and risk of major bleeding. However, this technique allows the best surgical exposure with complete access to the entire outflow graft, allowing for revision of the inflow cannula angle relative to the heart, if needed. The use of a sternal-sparing less invasive approach through a left lateral thoracotomy with partial rib resection may also be feasible [29]. However, this approach implies a smaller surgical field with more difficult access to anatomic structures. This is the purpose for the presence of a longer remnant of the HVAD (Medtronic, Framingham, MA) outflow graft after LVADE: graft-to-graft anastomosis is typically performed over the acute margin of the right ventricle just behind the sternum []. It is also possible to combine this surgical access with a right anterior thoracotomy at the third intercostal space for a direct anastomosis on the aorta. For specific devices, LVADE has also been performed with subcostal access, as is the case for the HM2, with a non-muscle dividing approach being associated with lower pain burden [30]. This approach is reasonable when there is no inflow and outflow involvement (such as

Table 2 Main factors to plan the surgical approach for left ventricular assist device exchange

Main factors defining surgical approach for LVADE
First implanted LVAD
Initial implant technique and surgical access
Patient's body habitus
Patient's clinical condition
Necessity of replacing the entire device or just one component (pump, driveline)
Indication for replacement
Extent of device damage
Need for concomitant cardiac procedure

obstruction) and there is no need for any concomitant cardiac procedure, since the pump is located in the abdomen. It is a less invasive procedure requiring shorter operative time, shorter cardiopulmonary bypass time, fewer blood transfusions, shorter intensive care unit stay, and less postoperative complications than re-sternotomy [31]. This surgical approach may increase the risk of postoperative device infections, although this has been mainly observed when an extended one-J-incision (incision extends from the xiphoid process to the left midclavicular line, with transection of the rectus muscles, fascia, and ribs) has been performed [32].

Regardless of the specific technique, a few key technical issues should be considered. First, it is of unique importance to verify the correct positioning and angle of the inflow cannula in order to adequately position the new sewing ring []. Second, obliteration of the dead space surrounding the new LVAD pump should be considered using soft tissue coverage of the pump pocket with a bulky vascularized pedicled flap of the greater omentum [20].

Regarding circulatory support during surgery, LVADE can be both performed on-pump and off-pump. When cardiopulmonary bypass is established, venous and arterial cannulas of the extracorporeal circulation are usually placed in the common femoral artery and vein. The main advantage of performing the procedure on-pump is allowing for careful inspection of the left ventricle chamber for thromboembolic material or remaining trabeculae tissue to mitigate recurrent thrombosis or stroke risk [33]. When the whole pump is exchanged, the new driveline should be tunneled to the opposite site of the former driveline exit site in an effort to reduce the risk of infective complications [33].

Postoperative care in patients undergoing LVADE exchange is similar to that of primary LVAD implantation. Special attention to the risk of bleeding due to adhesions or extensive surgery must be considered. This can be managed by strict monitoring and diligent management of anticoagulation, especially in patients who previously experienced device thrombosis [29].

A recent expert review summarizes the best available evidence to consider during LVADE from HVAD to HM3 []. It is important to underline specific technical issues that must be considered when performing LVADE with those devices. This is particularly important regarding the possibility to maintain the sewing ring and the outflow graft of the previous pump. Multiple solutions have been developed to assist in avoiding the traumatic complete removal of the device. The HVAD inflow cannula has a larger diameter (20.6 mm) when compared with the HM3 (20.5 mm). Currently, the best option is complete removal of the existing sewing ring. The use of a rubber seal to obtain hemostasis at the inflow connection has been described as an alternative, though the long-term consequences remain unknown. The possibility of sewing the HM3 apical connector over the existing HVAD sewing ring has also been described []. A drawback of this technique is that the tip of the inflow cannula will be less inside the LV reducing the LV unloading and consequently the LVAD flow.

Surgical adaptation of the outflow graft is possible and must be considered since the HVAD outflow prosthesis diameter is smaller than the outflow of the HM3 (10 mm vs. 14 mm, respectively). The anastomosis between the two outflow grafts must be done consequently. The optimal solution is still considered to be the exchange of the entire device, including the outflow graft, but in vivo and in vitro studies suggest that outcomes are not influenced by the slightly higher resistance caused by the lower diameter of HVAD outflow graft attached to the aorta [32, 34]. The safety of leaving portions of the infected LVAD in place has not been described. Ultimately, it is important to note the unknown clinical consequences of this procedure on hemocompatibility risks, battery runtime, and pump performance [].

Results

LVADE is associated with variable operative mortality, ranging from 7 to 10% [6, 10]. Survival rate following LVADE has been found to be non-inferior to conservative treatment group (93% vs. 76%, $p = 0.15$) [35]. In a recent study, postoperative mortality at 30 days was comparable for patients undergoing LVADE and primary implantation [19]. Causes of death are not particularly device-specific and, therefore, are usually related to patient medical history, management, and etiology of device dysfunction. While the rates of each cause of death are similar to those expected with primary implantation, patients requiring exchange may have increased risk of postoperative coagulopathy, with higher incidences of cerebro-vascular accident and pump thrombosis [19]. Among the various complications that can follow LVADE, the most prevalent appears to be right heart failure. In a recent study conducted by Austin et al., right heart failure occurred in 33% of the patients, with no difference in device technology [6]. A recent observational study showed that among candidates awaiting heart transplantation on a durable LVAD, undergoing pump exchange doubled the risk of 1-year mortality [36].

Table 3 summarizes large series published focusing on patients undergoing LVADE. From 2004 to 2021, a total of 19 manuscripts were published, ranging from first- to third-generation devices. A total of 935 patients were included. Main indications for exchange were thrombosis (56%), device malfunction (28.8%), device infection (10.9%), and outflow graft obstruction or inflow graft malposition (0.3%). Exchange using the same technology occurred in 441 patients (60.9%) while using a different technology occurred in 283 (39.1%). Surgical approach included redo-sternotomy

Table 3 Studies reporting patients undergoing Left ventricular assist device exchange

First author, year	Title	LVADE	Same technology (ST)-new technology (NT) LVADE	Indications	Study type	Access (sternotomy, thoracotomy, subcostal)	In-hospital mortality (30-day mortality)	Postoperative complications
Cogswell et al., 2021 [19]	HVAD to Heartmate 3 Device Exchange: A Society of Thoracic Surgeons Intermacs Analysis	45 (HVAD-HM3) 234 (HVAD-HVAD)	NT 45/279 (16%) ST 234/279 (84%)	Thrombosis 173 (57.6%), device malfunction 90 (30%), infections 23 (7.7%), other 14 (4.7%)	Retrospective STS Intermacs registry analysis	Not specified	38/279 (13.6%)	Infections 47 (16.7%), CRRT 46 (16.4%), 25 stroke (9%), 17 RVAD (6%)
Yost et al., 2021 [23]	Outcomes Following Left Ventricular Assist Device Exchange: Focus on the Impacts of Device Infection	64 (HM2-HM2); 7 (HW-HW), 1 (HW-HM2)	ST 71/72 (99%) NT 1/72 (1%)	Device malfunction 29 (40.3%), hemolysis/thrombosis 27 (37.5%), infection 13 (18.1%), other 3 (4.2%)	Single-center, retrospective	Redo-median sternotomy 65 (90.3%), 6 subcostal (8.3%), thoracotomy 1 (1.4%)	5/72 (6.9%)	Not specified
Imamura et al., 2020 [37]	Outcomes following left ventricular assist device exchange	13 HM2-HM2; 1 HVAD-HVAD; 1 HM2-HVAD	ST 14/15 (93%) NT 1/15 (/%)	Thrombosis 15 (100%)	Single-center, retrospective	Subcostal 13 (86.7%), Redo-sternotomy 2 (13.3%)	30-day mortality 0/15 (0%)	Not specified
Barac et al., 2020 [20]	Early Outcomes with Durable Left Ventricular Assist Device Replacement Utilizing the Heartmate III	85 (HM2/HVAD-HM2/HVAD) 30 (HM2/HVAD-HM3)	Not specified which kind of LVAD was present before or after LVADE	Thrombosis 63 (54.8%), infection 28 (24%), device malfunction 24 (21.2%)	Single-center, retrospective	Not specified	9/105 (8.6%)	RHF 21 (20.2%), CRRT 17 (16.3%)
Koda et al., 2020 [18]	Surgical device exchange provides improved clinical outcomes compared to medical therapy in treating continuous-flow left ventricular assist device thrombosis	28 (HM2- HM2)	ST 28/28 (100%)	Thrombosis 28 (100%)	Single-center, retrospective	Subcostal 17 (60.7%), redo-sternotomy 11 (39.3%)	1/28 (3.6%)	Sepsis 1 (3.6%)
Beaupre et al., 2019 [38]	Device exchange from Heartmate II to HeartWare HVAD	11 (HM2-HVAD)	NT 11/11 (100%)	Infection 6 (55%), device malfunction 3 (27%), thrombosis 2 (18%)	Single-center, retrospective	Redo-sternotomy 9 (82%), Subcostal 2 (18%)	30-day mortality 1/11 (9.1%)	HF requiring RVAD 3 (27%), bleeding requiring surgical re-exploration, 2 (18%)

Table 3 (continued)

First author, year	Title	LVADE	Same technology (ST)-new technology (NT) LVADE	Indications	Study type	Access (sternotomy, thoracotomy, subcostal)	In-hospital mortality (30-day mortality)	Postoperative complications
Agarwal et al., 2019 [21]	Clinical Experience of HeartMate II to HeartWare Left Ventricular Assist Device Exchange: A Multicenter Experience	24 (HM2-HVAD)	NT 24/24 (100%)	Thrombosis 22 (92%), infection 2 (8%)	Multi-center, retrospective	Redo-sternotomy 19 (79%), left anterior thoracotomy with subcostal approach 5 (21%)	30-day mortality 2/24 (8.3%)	HF requiring RVAD 2 (8.3%)
Yu et al., 2018 [35]	Late outcomes of subcostal exchange of the HeartMate II left ventricular assist device: a word of caution	41 (HM2-HM2)	ST 41/41 (100%)	Thrombosis 31 (75.6%), device malfunction 8 (19.5%), infection 2 (4.9%)	Single-center, retrospective	Subcostal 41 (100%)	0/41 (0%)	RHF 2 (4.9%), GIB 2 (4.9%), AKI 4 (9.8%), VT 5 (12.2%)
Hanke et al., 2018 [32]	Left ventricular assist device exchange for the treatment of HeartMate II pump thrombosis	16 (HM2-HM2)	ST 16/16 (100%)	Thrombosis 16 (100%)	Single-center, retrospective	Thoracotomy 16 (100%)	30-day mortality 4/16 (25%)	Bleeding requiring surgical re-exploration 5 (31.3%), stroke 5 (31.3%), infection 4 (25%), CRRT 4 (25%), HF requiring V-A ECMO 3 (18.8%), RHF 2 (12.5%), re-thrombosis 1 (6.3%)
Tchantchaleishvili et al., 2017 [33]	Subxiphoid Exchange of HeartMate II Left Ventricular Assist Device	30 (HM2-HM2)	ST 30/30 (100%	Thrombosis 22 (73.3%), device failure 5 (16.7%), outflow graft obstruction 2 (6.7%), inflow graft malposition 1 (3.3%	Single-center, retrospective	24 (80%) subcostal, redo-sternotomy 6 (20%)	90-day mortality 3/30 (10%)	Stroke 4 (13.3%)
Shaikh et al., 2016 [39]	HeartMate II Left Ventricular Assist Device Pump Exchange: A Single-Institution Experience	16 (HM2-HM2)	ST 16/16 (100%)	Thrombosis 15 (93.8%), infection 1 (6.2%)	Single-center, retrospective	Redo-sternotomy 9 (56.2%), subcostal 7 (43.8%)	1/16 (6.2%)	HF requiring V-A ECMO 1 (6.3%)

Table 3 (continued)

First author, year	Title	LVADE	Same technology (ST)-new technology (NT) LVADE	Indications	Study type	Access (sternotomy, thoracotomy, subcostal)	In-hospital mortality (30-day mortality)	Postoperative complications
Levin et al., 2015 [40]	Device Exchange in HeartMate II Recipients: Long-Term Outcomes and Risk of Thrombosis Recurrence	37 (HM2-HM2)	ST 37/37 (100%)	Thrombosis 23 (62.2%), device malfunction 13 (35.1%), infection 1 (2.7%)	Single-center, retrospective	Sternotomy 1 (2.7%), Redo-sternotomy 16 (43.2%), subcostal 20 (54.1%)	2/37 (5.4%)	Not specified
Anand et al., 2015 [41]	Continuous-flow ventricular assist device exchange is safe and effective in prolonging support time in patients with end-stage heart failure	77 (HM2/Jarvik 2000/HVAD—HM2/Jarvik 2000/HVAD)	*Not specified which kind of LVAD was present before or after LVADE*	Hemolysis/thrombosis 49 (63.6%), infection 9 (11.7%), other 19 (24.7%)	Single-center, retrospective	Left subcostal 40 (51.9%), redo-sternotomy 31 (40.3%), left thoracotomy 6 (7.8%)	30-day mortality 3/66 (4.5%)	Not specified
Ota et al., 2014 [42]	Continuous-flow left ventricular assist device exchange: clinical outcomes	30 (HM2-HM2)	ST 30/30 (100%)	Thrombosis 19 (63.3%), device malfunction 9 (30%), infection 2 (6.7%)	Single-center, retrospective	Subcostal 16 (53.5%), redo-sternotomy 14 (46.7%)	2/30 (6.7%)	Driveline infection 2 (6.6%), Pneumonia 1 (3.3%), CRRT 1 (3.3%), TIA/stroke 3 (10%), RHF requiring RVAD 2 (6.7%), GIB 2 (6.7%)
Moazami et al., 2013 [10]	Pump Replacement for Left Ventricular Assist Device Failure Can Be Done Safely and Is Associated With Low Mortality	73 (HM2-HM2) 4 (HM2-XVE)	ST 73/77 (95%) NT 4/77 (5%)	Device malfunction 35 (45.6%), thrombosis 24 (31.6%), infection 7 (8.9%), other 10.7 (13.9%)	Multi-center, retrospective	Redo-sternotomy 54 (70.1%), subcostal 20 (26%), unreported 3 (3.9%)	30-day mortality 5/77 (6.5%)	Bleeding requiring surgical re-exploration 7 (9.1%), RHF requiring RVAD 1 (1.3%), stroke 5 (6%), infection 3 (4.5%)
Adamson et al., 2009 [24]	HeartMate Left Ventricular Assist System Exchange: Results and Technical Considerations	19 (HM IP/VE/XVE/HM2—HM VE/XVE/HM2)	*Not specified which kind of LVAD was present before or after LVADE*	Device malfunction 15 (78.9%), infection 4 (21.1%)	Single center, retrospective	Redo-sternotomy 17 (89.5%), abdominal approach 2 (10.5%)	0/19 (0%)	Not specified

Table 3 (continued)

First author, year	Title	LVADE	Same technology (ST)-new technology (NT) LVADE	Indications	Study type	Access (sternotomy, thoracotomy, subcostal)	In-hospital mortality (30-day mortality)	Postoperative complications
Gregoric 2008 [31]	Exchange Techniques for Implantable Ventricular Assist Devices	6 HeartMate (VE or XVE)-XVE 8 HeartMate (VE or XVE)-HM2 4 Jarvik 2000-Jarvik 2000 1 HM2-HM2	ST 11/19 (57.9%) NT 8/19 (42.1%)	Device malfunction 13 (68.4%), hemolysis/thrombosis 5 (26.3%), infection 1 (5.3%)	Single center, retrospective	Sternotomy 19 (100%)	2/19 (10.5%)	Not specified
Dembitsky et al., 2004 [7]	Left ventricular assist device performance with long-term circulatory support: lessons from the REMATCH trial	29 (HMVE-HMVE)	ST 29/29 (100%)	Device malfunction 26 (89.7%), infection 3 (10.3%)	Multi-center, unblinded randomized clinical trial (prospective)	Not specified	5/22 (22.7%), 30-days mortality	Infection 9 (31%), device failure. 4 (13.5), stroke 3 (9.1%)

AKI, acute kidney injury with or without CRRT; *RHF*, right heart failure; *CRRT*, complete renal replacement therapy; *VT*, ventricular tachycardia; *DH*, DuraHeart; *HM IP*, HeartMate Implantable Pneumatic; *HM VEXVE*, Vented Electric/eXtended Vented Electric

(53.1%), subcostal incision (40.2%), thoracotomy (4.5%), left anterior thoracotomy with subcostal approach (0.9%), abdominal (0.4%), or first sternotomy (0.20%). Complications included acute kidney injury (10.3%), infection (9.6%), right heart failure requiring right ventricular assist device (RVAD) (7.2%), stroke (6.5%), bleeding (2.0%), refractory ventricular tachycardia (0.7%), GIB (0.6%), device failure (0.6%), and heart failure requiring postoperative extracorporeal membrane oxygenation (ECMO) (0.6%). Overall mortality was 8.8%.

Table 4 summarizes reports of LVADE cases series (< 10 patients). From 2012 to 2019, 6 studies with a total of 37 patients were included. Main indications for device exchange were thrombosis (51.3%), device infection (24.3%), driveline-related device malfunction (18.9%), and non-driveline-related device malfunction (5.4%). Exchange using a different technology was chosen in 25 patients (67.6%), while using the same technology occurred in 12 patients (32.4%). Surgical approaches included redo-sternotomy (29.4%), subcostal incision (26.5%), and thoracotomy (44.1%). Overall mortality was 8.1% (3/37).

Discussion

LVADE can be performed safely and with low surgical mortality using the same generation pump or exchanging in favor of a more recent device [6, 10, 11]. Although there are currently no guidelines as to the best strategy for LVADE, the choice of new device should be tailored to the individual patient's risk profile, considering the patient's unique factors and comorbidities [6]. This is particularly prudent when it is not possible to define the specific etiology prompting LVADE. Patients that develop complications despite optimal anticoagulation, antiplatelet therapy, appropriate pump speed and flow, and no other signs of infection are prone to develop the same complication after LVADE with a pump of the same generation [47]. It is also important to consider the specific risk profile of every device. Data suggesting improved stroke rate outcomes with the HeartMate 3 help inform device exchange choice in cohorts of patients at an increased risk of cerebrovascular events. Due to the improved hemocompatibility profile, LVAD upgrade to HM3 is attractive for patients with recurrent device thromboses [33]. It should be noted that data from the MOMENTUM 3 trial suggests improved survival benefit with HM3 compared to HVAD for LVADE regardless of primary implantation or device exchange. There are also some complications that have similar incidences in different devices, including right heart failure. In this case, the most important consideration is optimizing perioperative patient management to reduce this risk [6]. This discussion is now strongly influenced by the recent recall of the HVAD from the Food and Drug

Table 4 Case series reporting patients undergoing left ventricular assist device exchange

First author, year	Title	LVADE[a]	Same technology (ST)-new technology (NT) LVADE	Indication	Study type	Access (sternotomy, thoracotomy, subcostal)	In-hospital mortality	Postoperative complications
Potapov et al., 2012 [43]	Pump Exchange for Cable Damage in Patients Supported With HeartMate II Left Ventricular Assist Device	5 (HM2-HM2)	NT 5/5 (100%)	Device malfunction (driveline damage) 5 (100%)	Single-center, retrospective	Subcostal 5 (100%)	0/5 (0%)	Not specified
Levy et al., 2014 [25]	Left ventricular assist device exchange for persistent infection: a case series and review of the literature	3 (HM2-HM2); 1 (HM1-HM1)	ST 4/4 (100%)	Infection 4 (100%)	Case series	Not specified	1/4 (25%)	Not specified
Takeda et al., 2019 [44]	Device exchange from HeartMate II to HeartMate 3 left ventricular assist device	9 (HM2-HM3)	NT 9/9 (100%)	Thrombosis 8 (88.9%), driveline damage 1 (11.1%)	Single-center, retrospective	Thoracotomy 8 (88.9%), sternotomy 1 (11.1%)	0/9 (0%)	Prolonged intubation > 48 h 2 (22.2%), bleeding 1 (11.1%), pneumonia 1 (11.1%), inflow malposition 1 (11.1%)
Tsubota et al., 2017 [9]	Left ventricular assist device exchange: the Toronto General Hospital experience	7 (HM2-HM2) 1 (HVAD-HVAD) 1 (DH-HM2)	ST 8 (88.9%) NT 1 (11.1%)	Thrombosis 6 (66.7%), device malfunction 2 (22.2%), driveline damage 1 (11.1%)	Single-center, retrospective	Sternotomy 5 (55.6%), subcostal 4 (44.4%)	30-day mortality 1/9 (11.1%)	Not specified
Gallo et al., 2017 [45]	Surgical Technique for Ventricular Device Exchange: From HeartMate II to HVAD	4 (HM2-HVAD)	NT 4 (100%)	Hemolysis/thrombosis 4 (100%)	Single-center, retrospective	Sternotomy 4 (100%)	1/4 (20%)	Not specified
Hanke et al., 2016 [46]	First series of left ventricular assist device exchanges to HeartMate 3	4 (HM2-HM3) 2 (HVAD-HM3)	NT 6 (100%)	Driveline infection 4 (66.6%), device infection 1 (16.6%), pump thrombosis 1 (16.6%)	Single-center, retrospective	Thoracotomy 6 (100%)	0/6 (0%)	Respiratory failure 2 (33.3%), stroke 1 (16.6%) CRRT 2 (33.3%)

AKI, acute kidney injury with or without CRRT; *RHF*, right heart failure; *CRRT*, complete renal replacement therapy; *VT*, ventricular tachycardia; *DH*, DuraHeart; *HM IP*, HeartMate Implantable Pneumatic; *HM VE/XVE*, Vented Electric/eXtended Vented Electric

Administration (FDA) on June 3, 2021, which made the HM3 the only commercially available device at the moment [37]. The reasons for this were both delay or failure to restart after elective or accidental discontinuation of pump operation and the higher reported risk of stroke and all-cause mortality in HVAD recipients [27]. In particular, LVADE to the HM3 compared with exchange to an HVAD demonstrated superior late survival with the former, but using this strategy in elective, uncomplicated cases is not currently supported by enough evidence. The risk of death due to LVADE likely exceeds the risk of death remaining on a normally functioning HVAD device [11].

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Declarations

Ethics approval Not required as it is a review article.

Statement of human and animal rights The human and animal rights were respected and abided during the course of the study.

Conflict of interest The authors declare that there is no conflict of interest.

Informed consent Not applicable being a review article and no patient identifying material.

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