Circulation

AHA SCIENTIFIC STATEMENT

Device Therapy and Arrhythmia Management in Left Ventricular Assist Device Recipients

A Scientific Statement From the American Heart Association

ABSTRACT: Left ventricular assist devices (LVADs) are an increasingly used strategy for the management of patients with advanced heart failure with reduced ejection fraction. Although these devices effectively improve survival, atrial and ventricular arrhythmias are common, predispose these patients to additional risk, and complicate patient management. However, there is no consensus on best practices for the medical management of these arrhythmias or on the optimal timing for procedural interventions in patients with refractory arrhythmias. Although the vast majority of these patients have preexisting cardiovascular implantable electronic devices or cardiac resynchronization therapy, given the natural history of heart failure, it is common practice to maintain cardiovascular implantable electronic device detection and therapies after LVAD implantation. Available data, however, are conflicting on the efficacy of and optimal device programming after LVAD implantation. Therefore, the primary objective of this scientific statement is to review the available evidence and to provide guidance on the management of atrial and ventricular arrhythmias in this unique patient population, as well as procedural interventions and cardiovascular implantable electronic device and cardiac resynchronization therapy programming strategies, on the basis of a comprehensive literature review by electrophysiologists, heart failure cardiologists, cardiac surgeons, and cardiovascular nurse specialists with expertise in managing these patients. The structure and design of commercially available LVADs are briefly reviewed, as well as clinical indications for device implantation. The relevant physiological effects of long-term exposure to continuous-flow circulatory support are highlighted, as well as the mechanisms and clinical significance of arrhythmias in the setting of LVAD support.

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Left ventricular assist devices (LVADs) improve survival and minimize morbidity in patients with end-stage heart failure (HF).[1–5] The clinical use of LVADs has steadily increased in the United States over the past several years.[6] Atrial arrhythmias (AAs) and ventricular arrhythmias (VAs) are common in LVAD recipients, which are likely mediated by the combination of preexisting abnormal myocardial substrate and complex electrical remodeling after LVAD implantation.[7–13] Important knowledge gaps pertaining to arrhythmias in LVAD recipients remain. The impact of sustained AAs and VAs on clinical end points in LVAD recipients is incompletely understood. In addition, the vast majority of patients who receive an LVAD for end-stage cardiomyopathy have a cardiovascular implantable electronic device (CIED), and it is common practice to maintain CIED detection and defibrillator therapies after LVAD implantation.[14] Data supporting the efficacy of an implantable cardioverter-defibrillator (ICD) and cardiac resynchronization therapy (CRT) in LVAD recipients, however, have been conflicting.[7,8,15–17] Moreover, how best to program CIED therapy after LVAD implantation is unknown. With regard to arrhythmia management and CIED use, the patient with an LVAD presents a very different physiological state compared with the patient with advanced HF, and optimal management strategies in this growing population need to be clarified. Prior guidelines[18] have not comprehensively addressed this topic.

The goal of this scientific statement is to provide a concise review of available scientific evidence and to provide clinical guidance from an expert group of cardiac electrophysiologists, HF/LVAD specialists, cardiac surgeons specializing in mechanical circulatory support, and cardiovascular nursing specialists on how to manage CIEDs, AAs, and VAs in the LVAD population, with the aim of optimizing arrhythmia care. Available evidence includes 1 randomized trial, retrospective and prospective observational data, and meta-analyses. We address gaps in knowledge and identify important areas for future collaborative research.

The writing group performed a comprehensive literature search (MEDLINE, EMBASE, Cochrane Library); identified relevant original articles, any applicable guideline and scientific statements, review articles, and meta-analyses; and developed recommendations that are based on data from the current literature. The intended audience for this statement is healthcare professionals, specifically those who are involved in the care of LVAD recipients.

LVADS: GENERAL CHARACTERISTICS

The current generation of LVADs have a number of basic components in common: an inflow cannula commonly inserted in the left ventricular (LV) apex that drains blood from the LV to the pump; an electrically actuated continuous-flow (CF) pump with a single rotating impeller suspended within a tube that propels blood forward by spinning the impeller at high speeds; and an outflow cannula that carries blood back to the arterial circulation, typically by way of the ascending aorta.[19,20] The power supply for the LVAD is a percutaneous lead that traverses the skin and connects the external power system with the internal pump. The external components of an LVAD system generally consist of a power source (ie, batteries or an alternating current power unit) and a small portable controller that controls pump speed and monitors device function. CF-LVADs can be of axial design, such as the HeartMate II (Abbott Labs, Chicago, IL), or centrifugal design, such as the HVAD (Medtronic, Inc., Minneapolis, MN) and HeartMate 3 (Abbott Labs, Chicago, IL) (Figure 1).[3,4,21] Blood flow through all CF-LVADs is directly proportional to pump speed and inversely related to the pressure difference across the inlet (LV pressure) and outlet (aortic pressure) orifices of the pump. CF through the pump occurs throughout the cardiac cycle; however, there are phasic changes in pump flow with greater flow during native cardiac systole than diastole because native LV contraction raises intracardiac pressure, thereby lowering the pressure gradient (the difference between aortic and LV pressures) that the pump must overcome to generate forward flow.[19,20] These phasic changes in blood flow impart a pulse, although diminished compared with a native cardiac contraction or a pulsatile-flow pump, to the native circulation. In circumstances in which there is an absence of native cardiac contraction (eg, ventricular fibrillation [VF]), the flow through a CF-LVAD is nonpulsatile.

Typically, centrifugal pumps tend to have a pressure-flow relationship that results in a greater degree of flow variability across the cardiac cycle (less flow in diastole and more flow in systole).[19,20] In theory, this results in centrifugal pumps having a greater aortic pulse pressure and less propensity to create LV collapse or a "suction event."

Indications for Use

Currently, there are 2 accepted indications for implantation of a durable LVAD that are recognized by the US Food and Drug Administration and for which there are reimbursement criteria set by the Centers for Medicare & Medicaid Services through a National Coverage Decision: bridge to transplantation (BTT) and destination therapy (DT; permanent pump implantation in patients not eligible for cardiac transplantation).[22,23] Patients meeting the indications for BTT or DT have advanced or end-stage HF (New York Heart Association class IIIB or IV symptoms) refractory to optimal medical management, with a majority requiring intravenous inotrope therapy or short-term mechanical circulatory support to manage symptoms or to stabilize hemodynamics

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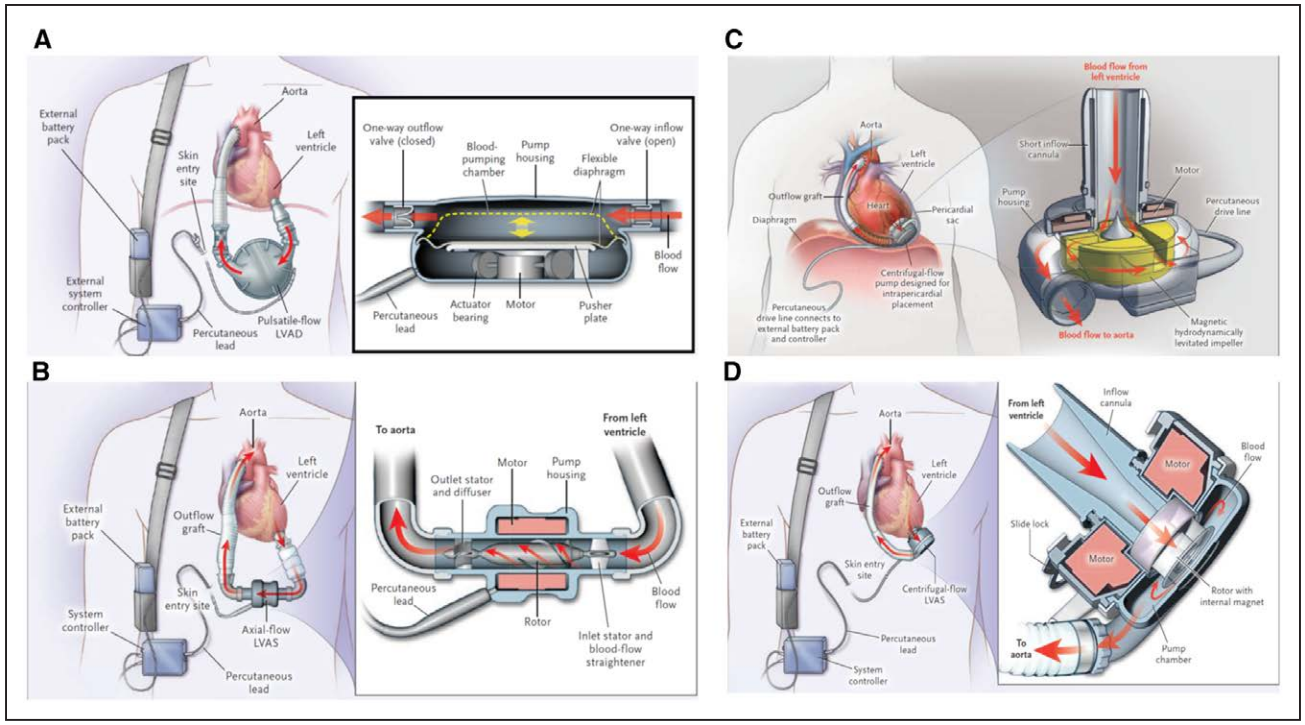

Figure 1. Diagrams demonstrating the various types of left ventricular assist devices (LVADs).
A, A pulsatile-flow LVAD. Reprinted from Slaughter et al[4] with permission from Massachusetts Medical Society. Copyright © 2009, Massachusetts Medical Society. **B** through **D,** Continuous-flow LVADs. **B**, An axial-flow pump in which blood enters at one end of the rotor and is driven along the axis of the rotor to the outflow of the pump. LVAS indicates left ventricular assist device. Reprinted from Slaughter et al[4] with permission from Massachusetts Medical Society. Copyright © 2009, Massachusetts Medical Society. **C** and **D**, Examples of centrifugal pumps. **C**, A compact centrifugal-flow intrapericardial LVAD that incorporates a bearingless design with magnetic and hydrodynamic levitation of the internal impeller. Reprinted from Rogers et al[21] with permission from Massachusetts Medical Society. Copyright © 2017, Massachusetts Medical Society. **D**, A fully magnetically levitated centrifugal-flow pump. Reprinted from Mehra et al[3] with permission from Massachusetts Medical Society. Copyright © 2017, Massachusetts Medical Society.

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and improve organ function before LVAD implantation (INTERMACS [Interagency Registry of Mechanically Assisted Circulation] patient profiles 1–3).[6] Patients receiving LVADs as BTT are generally listed for cardiac transplantation or have been evaluated for transplantation and have no absolute contraindications.[23] Currently, the National Coverage Decision set forth by the Centers for Medicare & Medicaid Services requires listing for heart transplantation as a prerequisite for patients to receive a durable LVAD for BTT indication, although this requirement is not universally recognized by all payers.[23] The paradigms of BTT and DT have become integrated into the treatment algorithm, but these paradigms do not consistently describe all clinical situations or the real-world realities of patient care, and the division of patients into BTT and DT populations has been problematic.[24] It is likely that indications for LVAD therapy will continue to evolve in the future.[3,24,25]

CF-LVAD PHYSIOLOGY AND POTENTIAL IMPLICATIONS FOR ARRHYTHMIAS AND CIEDS

CF-LVAD therapy is associated with physiological (mal)adaptations that may manifest clinically as hypertension, gastrointestinal bleeding, pump thrombus, and stroke.[26–28]

The absence of a physiological pulse results in patients with a CF-LVAD having very high levels of sympathetic nerve activity[29] from baroreceptor unloading.[26] This may contribute to difficult-to-control blood pressures and overt hypertension through α_1 receptor–mediated increases in total peripheral resistance.[27] In addition, the renin-angiotensin axis is upregulated in the setting of CF-LVAD support, as suggested by a decline in plasma renin activity.[30] On a cellular level, CF-LVADs lead to endothelial dysfunction, which occurs early after CF-LVAD implantation, worsens over time, and is associated with adverse cardiovascular events in this population.[31]

The rotating impeller within the CF-LVAD creates a high level of local shear stress on blood and plasma products as they travel through the device, resulting in an acquired von Willebrand syndrome, contributing to a higher rate of bleeding events in these patients.[28] This issue is particularly problematic because these patients receive anticoagulants as standard of care.[32] Thus, otherwise routine procedures such as CIED implantations and pulse generator changes can become challenging in the patient with a CF-LVAD.

As a result of the risks associated with long-term exposure to CF circulatory support, many groups have advocated reducing LVAD pump speed as much as possible to enhance pulsatile flow.[26] Upward or downward adjustments in LVAD pump speed, however, are often necessary to accommodate fluctuations in hemodynamics or changes in medications.[33] In this setting, care must be taken to ensure that ventricular geometry is not significantly altered as a result of modulations in speed. For example, large increases in pump speed will unload the LV and may predispose to suction events, which can precipitate VAs.[34] Furthermore, excessively high speeds may precipitate right ventricular (RV) dysfunction or overt RV failure because septal migration toward the LVAD inflow cannula leads to an increase in RV diameter and wall stress, as well as a reduction in septal contribution to RV systolic function. Conversely, reductions in pump speed will enhance pulsatility by allowing the LV to contribute more to total cardiac output.[26] However, excessive reductions in pump speed may precipitate left HF.

EPIDEMIOLOGY, MECHANISMS, AND SIGNIFICANCE OF ARRHYTHMIAS IN LVAD RECIPIENTS

VAs and Sudden Cardiac Death

VAs are common after LVAD implantation, although the incidence varies depending on the underlying type of cardiomyopathy, existence of preoperative VA, type of LVAD, arrhythmia surveillance method, definition of VA, and length of follow-up.[10,35–41] Observational series reporting the occurrence of VA in LVAD recipients describe a high burden, ranging from 20% to 50% of patients,[10,35–37,39,40,42] and ICD shocks in 16% to 42% of LVAD recipients.[40,41,43–46] LVAD recipients are at an increased risk of developing de novo monomorphic ventricular tachycardia (VT), regardless of whether they had VT before LVAD implantation.[4,39,36] One study observed new-onset monomorphic VT in 18% of LVAD recipients, an incidence 4.5 times higher than suppression of previously present monomorphic VT.[36] Despite tremendous changes in LVAD technology, the time course of VA appears to have remained consistent: VAs occur more frequently in the early postoperative period and decrease over the first weeks to months after implantation.[10,35,36,42,47,48] The most powerful predictor of post-LVAD VA is having experienced VA before LVAD implantation, although de novo VA is well described.[8,10,36,39,41,49]

Several multivariate observational analyses have shown an association of ischemic cardiomyopathy with VA during LVAD support,[36,37,47] whereas others have noted increased risk in patients with nonischemic cardiomyopathy.[41] The use of β-blocker therapy in patients with an LVAD has been associated with a significantly reduced risk of VA in 1 observational study.[40] Data also suggest that the incidence of VA may be greater in patients with CF-LVADs, although the population of patients undergoing LVAD implantation has shifted during this technological transition.[42,43]

Proposed mechanisms of VA vary by patient population and duration of LVAD support and include ischemia, fibrosis, inotropic and pressor therapies, mechanical induction from the inflow cannula, suction events, or other unclear reasons of proarrhythmia.[37,50,51] Reduced myocardial stress, the result of ventricular unloading from the LVAD, may result in a decrease in QRS duration and increased QTc after LVAD implantation.[52] Further electrophysiological remodeling is seen over time, resulting in a delayed decrease in QTc interval corresponding to a decreased action potential duration in the weeks to months after LVAD placement.[52] The immediate postoperative period may therefore be marked by increased VA as a result of relative electrophysiological instability. Short-term changes in action potential duration, heterogeneity of repolarization, prolongation of QTc, and altered refractoriness may all contribute to the substrate for reentry or triggered activity.[47] Electrolyte shifts in the postoperative period[53] and changes in ion channel expression[40] also appear to play a role in triggering VA episodes.[54] Preexisting myocardial structural disease remains fundamental to the substrate for VA; the majority of mapped VTs during longer-term LVAD support are related to intrinsic scar rather than the inflow cannula.[12,50] Thus, it is important to understand that the LVAD per se is not a treatment for VT and that the majority of VTs result from underlying substrate, not from HF and worsening hemodynamic status.

The impact of VA in this patient population is variable. Early observational studies of patients with an LVAD support noted good tolerance of VA (Figure 2), with symptoms of weakness or palpitation, but no syncope, and substantial protection from sudden cardiac death.[56–58] LVAD flow decreased during VA, but overall, the absence of RV contraction did not result in significant morbidity.[56,57] Tolerance of even persistent VF may be greater in CF-LVADs because output is less sensitive to filling pressures of the native heart.[59,60] Concerns remain about the effects of reduced pump flow resulting from lower preload in fixed-speed centrifugal-flow pumps, adverse effects on RV function caused by sustained VAs, and the potential for thrombosis in a fibrillating RV.[59]

The relationship between VA after LVAD implantation and mortality is difficult to ascertain. Many observational series have shown an association between VAs and mortality, particularly when VA occurs in the early postoperative period.[37,61–63] However, this association is

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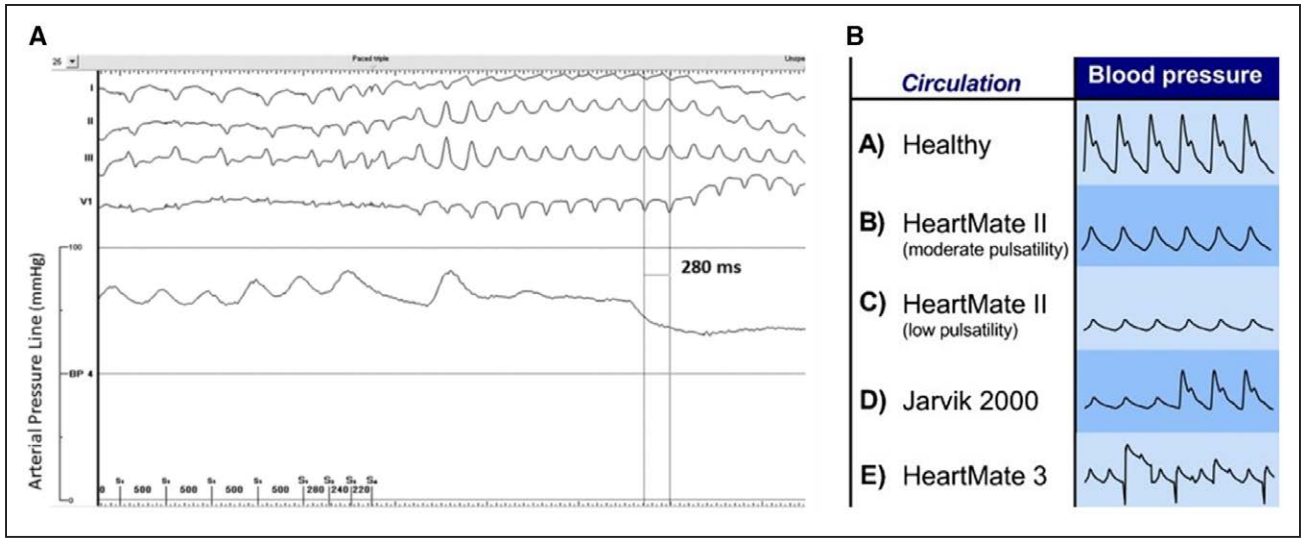

Figure 2. Left ventricular assist device (LVAD) support and hemodynamics during sustained ventricular tachycardia (VT).
A, Programmed ventricular stimulation in a patient with an LVAD and dilated cardiomyopathy. Arterial pressure line is displayed (BP 4). Note the low pulsatility during baseline rhythm. When a fast VT is induced (214 beats per minute), the pulse pressure disappears, but mean arterial pressure remains at ≈70 mm Hg, and the patient is asymptomatic, which allows safe mapping of the induced VT. Reprinted from Sacher et al.[12] Copyright © 2015, American Heart Association, Inc. **B**, Typical arterial blood pressure waveforms in healthy individuals and different types of LVADs are shown for comparison. Reprinted from Castagna et al.[55] Copyright © 2017, The Authors. Published on behalf of the Authors by Springer US. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http:/creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

not consistent,[10] and it is unknown whether this is truly causal or if VA is simply a marker of an overall increased risk of death resulting from competing causes. A recent meta-analysis of 9 observational studies including 1179 patients revealed an association of post-LVAD VA and mortality and demonstrated that pre-LVAD VA is a major risk factor for mortality.[64] The authors note that these results should be considered hypothesis generating, a rational conclusion given the low risk of sudden cardiac death in this population.[59] In an analysis of data from the INTERMACS registry, arrhythmias were not found to be a predictor of mortality.[6] Evidence suggests that the incidence of post-LVAD VAs has been decreasing over the past decade.[62]

Atrial Arrhythmias

Compared with data on VA and sudden cardiac death, less is known about the incidence and impact of AAs in patients with LVADs. Unsurprisingly, the prevalence of preexisting AAs, particularly atrial fibrillation (AF), and the incidence of post-LVAD AAs are high. AAs are diagnosed in 21% to 54% of patients before LVAD implantation, the majority with AF and a minority with atrial flutter and atrial tachycardia.[11,65–67] Non-AF AAs coexist in many patients, including atrioventricular nodal reentrant tachycardia.[65] Although the strongest predictor of post-LVAD AF is preimplantation AF, ≈20% to 30% of patients will develop de novo AF after LVAD implantation.[11,65] AF was seen to remit in 43% of patients after LVAD implantation, a finding likely related to salutary reductions in left atrial size and volume.[65] Female sex may be a risk factor for incident AF after LVAD.[65] Unexpectedly, postoperative AF is not strongly associated with an overall increased risk of mortality or stroke in these observational series after adjustment for clinical variables.[11,65–69] However, a high burden of AF may portend a worse outcome. In subgroup analyses, persistent AF was associated with a combined end point of HF and death[66] or with a nonsignificant trend toward reduced survival.[65] Concordant with findings in the non-LVAD population, patients with an LVAD with AF may have a higher risk of developing post-LVAD VA, potentially as a result of worsened myocardial vulnerability to arrhythmia initiation.[49] Hottigoudar et al[70] reported a case series of 8 patients with the HeartMate II LVAD who developed de novo sustained atrial flutter that led to decompensated right HF, which completely resolved with catheter ablation. Although the study was not controlled, the results are suggestive of the potential hemodynamic impact from sustained AA in LVAD recipients.

A major concern in the population of patients with an LVAD is the risk of thromboembolic events. Clinical data on whether AF increases this risk are conflicting. Although preoperative AF has been associated with increased risk of thromboembolism,[68] other studies have found a reduced association[66] or no increased risk.[67,69,71] No clinical trial data are currently available to support decision making with respect to target international normalized ratio, left atrial appendage procedures, or rhythm control strategies.

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MANAGEMENT OF CIEDS IN LVAD RECIPIENTS

ICD and Survival in LVAD Recipients

ICD therapy has been shown to improve survival when used for the primary prevention of sudden cardiac death in patients with HF symptoms and severe LV dysfunction, as well as for secondary prevention of sudden death in patients with previously documented sustained VAs.[72–74] Given a history of advanced HF, most LVAD recipients either already have an ICD at time of LVAD implantation or are candidates to receive one. VAs may continue to occur after LVAD implantation, with a high incidence during the first 30 days after implantation. Those with documented VAs before LVAD implantation are at especially high risk.[40,75] However, it is not entirely clear if ICDs contribute to improved survival after an LVAD has been implanted because patients supported by LVADs may tolerate sustained VAs with minimal hemodynamic instability given the ability of the LVAD to maintain cardiac output during arrhythmic events.[56]

The evidence on whether ICDs offer a survival advantage to patients with an LVAD has been mixed. In 2 early studies, Refaat et al[45] and Cantillon et al[8] reported a survival advantage in patients with an LVAD and ICD versus no ICD. However, the majority of patients in these 2 studies received pulsatile devices; therefore, the results may not apply to current-generation CF-LVADs. Enriquez et al[16] reported their experience with 106 patients who received a CF-LVAD; VAs occurred in 34.9%, and appropriate shocks were given in 27.3% of patients, but the presence of an active ICD was not associated with improved survival (hazard ratio [HR], 1.12 [95% CI, 0.37–3.35]). Garan et al[39] reported their single-center experience with CF-LVADs and VAs in 94 patients, of whom 77 had an ICD (5 had the device deactivated) and 17 did not. Twenty-two patients had a VA >30 days after LVAD implantation; the strongest predictor was preexisting VA. No patients discharged from the hospital without an ICD after CF-LVAD implantation died during 276.2 months of follow-up (mean time without ICD, 12.7±12.3 months). Lee et al[46] reported their experience in 100 patients who underwent CF-LVAD implantation. Death occurred in 18 patients (30%) in the ICD group versus 15 (38%) in the no ICD group. However, after 1 year, there was no statistically significant benefit from ICD therapy in patients with an LVAD (*P*=0.56), and no patient had a sudden cardiac death. Likewise, a study of the United Network for Organ Sharing registry for patients with an LVAD examining the relationship between the presence of an ICD and wait list mortality in 1444 patients did not show a difference in mortality in the ICD group. Notably, only 7 deaths attributed to arrhythmia occurred: 2 in the ICD group and 5 in the non-ICD group.[76] Similarly, a propensity analysis of 2990 BTT patients from the United Network for Organ Sharing registry did not show a difference in survival with adjustment for complications in patients with an LVAD with and without an ICD.[61] A recent propensity score–matched comparison of 2209 patients with a CF-LVAD from the INTERMACS registry with and without an active ICD showed that the presence of an ICD was associated with an increased mortality risk (HR, 1.20 [95% CI, 1.04–1.39]; *P*=0.013) and an increased risk of unexpected death during LVAD support (HR, 1.33 [95% CI, 1.03–1.71]; *P*=0.03).[77]

Agrawal et al[78] conducted a meta-analysis of the impact of ICD therapy on mortality in CF-LVAD recipients; the analysis included 3 studies with a total of 292 patients (203 [69.5%] with ICD versus 89 [30.5%] without ICD). The presence of an active ICD was associated with an odds ratio for survival of 0.63 but with a 95% CI of 0.33 to 1.18, which was not statistically significant (*P*=0.15). A second meta-analysis of 6 studies (937 patients) showed that ICD therapy was associated with decreased mortality, but this finding was not significant in patients with CF-LVADs.[15]

Thus, we can conclude that there are insufficient data to claim a survival advantage in patients with LVADs who receive ICDs, yet the decision to implant can be individualized on a case-by-case basis, with stronger consideration given to those patients with LVADs in whom VAs have been associated with hemodynamic compromise or other symptoms of hypoperfusion such as syncope or impaired LVAD flow. In view of the need for making individual considerations, the 2017 American Heart Association/American College of Cardiology/Heart Rhythm Society guidelines on VA provide a Class IIa recommendation for ICD implantation in patients with LVADs, stating that in patients with an LVAD and sustained VAs, an ICD can be beneficial.[79]

CRT and Outcomes in LVAD Recipients

Similar to ICDs, many patients with an existing CRT-defibrillator (CRT-D) continue biventricular pacing after LVAD implantation. It is possible that the unloaded LV after LVAD implantation is a target for CRT to aid myocardial recovery. So far, 2 published single-center observational studies, 1 recent multicenter study, and a small single-center randomized controlled study have addressed this question. Gopinathannair et al[7] compared continued CRT with ICD only in 61 patients with a CF-LVAD. Over a mean follow-up of 682±45 days of LVAD support, no significant differences were seen in survival, all-cause and HF hospitalizations, or incidence of VA and ICD therapies. Schleifer et al[17] compared the arrhythmic outcomes between patients with a CF-LVAD with continued CRT (CRT-on; n=39) and those who had CRT turned off (CRT-off; n=27) before discharge. CRT was turned off for phrenic nerve stimulation, lead mal-

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function, battery conservation, and infection requiring lead extraction. No significant differences in all-cause mortality, hospitalizations, VAs, inappropriate shocks, and ICD generator changes were noted between groups. The CRT-off group had a higher incidence of total ICD shocks per patient compared with the CRT-on group (5.5±9.3 vs 1.5±2.7; *P*=0.014).[17] A recent small randomized controlled trial of ICD programming in CF-LVAD recipients also randomized CRT devices to CRT-on (n=21) versus CRT-off (n=20). During follow-up, patients in the CRT-on group had fewer (10%) ICD shocks compared with those in the CRT-off group (38%), but this difference did not reach statistical significance (*P*=0.08). No changes were noted between the groups in inappropriate shocks, arrhythmic hospitalizations, and hospitalizations for HF.[80] More recently, Gopinathannair et al,[81] in a large multicenter study, compared continued CRT versus ICD only in 488 patients with a CF-LVAD and found no significant differences between groups in survival, all-cause and HF hospitalizations, VAs, and ICD shocks over a median follow-up of 478 days. Multivariate Cox regression demonstrated no survival benefit for type of device (ICD vs CRT-D; HR, 1.46; *P*=0.16). During follow-up, 69 patients (26%) underwent CIED pulse generator replacement in the CRT-D group compared with 36 (15.5%) in the ICD group (*P*=0.003).[81]

It is important to mention the limitations of the aforementioned data. All the studies evaluating the role of ICDs in LVAD recipients have been observational, the majority single center, and are therefore fraught with the potential for bias. ICD therapy was not randomized, so it is not clear why some patients received ICDs and others did not, and it is possible that patients who come to LVAD implantation without an ICD are a very different population than those who already have an ICD. In addition, there was no standardization of ICD programming, and the event rate was generally too low to make strong conclusions. Even the single-center randomized study that evaluated CRT-on versus CRT-off in LVAD recipients[80] had a small sample size and lacked adequate statistical power.

However, it seems that several premises are suitable for further examination. Although VAs are common among patients with CF-LVADs, they are not always necessarily life-threatening during ventricular assist device support. The bulk of the available data suggest that ICDs and CRT-Ds confer no significant survival benefit in patients with a CF-LVAD. It remains to be determined which subgroup of patients may benefit from aggressive antiarrhythmic therapies. CF-LVADs in particular appear to provide enough hemodynamic support to prevent sudden arrhythmic death in the absence of an ICD. ICD therapy is also not without risks, and ICD shocks can negatively affect quality of life and outcomes.[82] Determining the benefit of ICD therapy in this complex population with a high risk of associated complications is unlikely to be feasible without a larger randomized trial.

The subcutaneous ICD, lacking any transvenous leads, can be an option when a new ICD implantation is contemplated in the patient with a CF-LVAD. Although case reports have reported concomitant use of a subcutaneous ICD in patients with an LVAD,[83–85] no substantial data exist to assess the safety and efficacy of a subcutaneous ICD in this population. Areas of potential concern include surgical access given the proximity of the SICD system to the LVAD, electromagnetic interference from the LVAD,[84,86,87] and lack of antitachycardia pacing (ATP), which is very important in CF-LVAD recipients because sustained VT is remarkably well tolerated and early shock is mostly unnecessary.

Pacing indications in an LVAD recipient should be similar to those in a patient without an LVAD. There are no targeted studies on the role of rate-responsive atrial pacing in patients with an LVAD with chronotropic incompetence; however, it stands to reason that maintaining an adequate baseline and exercise heart rate aids proper LV filling. Loss of atrioventricular synchrony, from either sustained AA or complete atrioventricular block, can result in RV failure in LVAD recipients.[70,88] Atrioventricular synchronous pacing or correcting AAs can restore atrioventricular synchrony and improve RV function. Available evidence shows that high-percentage RV pacing in a patient with an LVAD may not be detrimental as in a patient with advanced HF[81]; however, prospective studies are needed to evaluate this further.

CIED-Related Issues and Complications After LVAD Implantation

Common Lead Parameter Changes After LVAD Implantation

Small retrospective studies comparing ICD function before and after LVAD implantation have demonstrated that up to 30% of ICD patients undergoing LVAD implantation experience a postoperative ICD-related adverse event.[89–91] These adverse events can include device-to-programmer interference, changes in lead pacing threshold, undersensing of VT/VF, lead fracture, sensing of electromagnetic noise, inappropriate arrhythmia detection and therapies, and increases in defibrillation thresholds resulting in unsuccessful ICD therapies.[90–95] Statistically significant postoperative decreases in RV sensing and impedances and increases in ventricular stimulation thresholds have been consistently observed.[89–91,96,97] The mechanisms of these lead parameter changes are poorly understood and may include mechanical lead disruption, changes in cardiac orientation caused by intraoperative organ manipulations or LVAD mass effects, shifts in lead orientation altering electrode contact, changes in LV size and septal

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shifting resulting from LV unloading, and myocardial inflammation, ischemia, or edema.[97] The majority of pacing threshold and sensing changes noted in these observational studies were of minimal clinical significance and may improve over time, although lead revisions after LVAD implantation for lead fractures, high capture thresholds, failure to cardiovert, and ventricular undersensing have been reported.[43,91,97] Given these findings, immediate postoperative ICD interrogation is recommended.

In addition to pacing and sensing parameter changes, other more serious postoperative ICD-related adverse events have been observed. These include inappropriate ICD therapies caused by electromagnetic interference by the LVAD on the ventricular sensing lead[90,91] and increases in defibrillation thresholds.[89,91] The latter has resulted in reported instances of failure to convert VAs both in clinical settings and during defibrillation threshold testing.[89,91] The mechanism of the rise in defibrillation thresholds after implantation is multifactorial and may be related to a change in heart geometry after LVAD implantation, vector shifts caused by the introduction of intrathoracic metal from the LVAD, and antiarrhythmic use.[89] The frequent use of amiodarone after LVAD implantation to suppress VAs is another possible factor because amiodarone use alone has been implicated in elevated defibrillation thresholds.[98,99]

The failure of device telemetry during both near-field and remote device interrogation sessions has also been reported, although it has been limited to older St. Jude Medical (Abbott Labs, Chicago, IL) and Sorin ICDs in combination with the HeartMate II LVAD.[92–94] This was caused by interference from the HeartMate II operating frequency on the communication band used to link the programmer telemetry to the CIED and often required generator replacement to restore communication. This interaction has not been observed with ICDs from other manufacturers, which operate at higher frequencies (Biotronik, 32 kHz; Medtronic, 175 kHz; Boston Scientific, 100 kHz). The wand telemetry on newer St. Jude devices operates at a 64-kHz frequency band, which is well outside the 7.2-kHz operating frequency of the HeartMate II LVAD, thereby eliminating most interference issues with the St. Jude system.[93] External electromagnetic interference has been reported with an LVAD and the ICD generator or the programming wand; placing aluminum shielding around the ICD programmer wand and steel shielding around the extension cable during ICD interrogation may protect this communication.[95,100]

As a result of these complications, up to 18% of patients with an ICD undergoing LVAD implantation require a postoperative ICD system modification.[91] System modifications have included lead revision, generator replacement, ICD reprogramming, or subcutaneous array implantation.[89,91,96] Because system parameter changes can evolve and improve over time after LVAD implantation, immediate invasive system modifications may not be necessary in the near-term post-LVAD implantation except in cases of life-threatening lead parameter changes (ie, loss of capture in a pacing-dependent patient).[97] Given the uncertainty about the survival benefit of ICD therapies in CF-LVADs, routine defibrillation threshold testing is not recommended after LVAD implantation but can be considered in select patients with high VA burden and failed ICD therapies. In case of high defibrillation thresholds after LVAD implantation, programming changes (changing vector polarity, adjusting tilt and pulse width of the biphasic shock wave form)[101–103] should be considered before the risk-benefit assessment of invasive approaches such as lead revision and subcutaneous coil implantation.

CIED Infections and Management in LVAD Recipients

LVAD infections are a common complication of LVAD implantation.[104] Management of LVAD driveline infections when ICD/CRT-D devices are present can be challenging, but educating providers, patients, and families on routine care is essential.[105,106] There is limited information on the incidence, clinical presentation, and outcomes of CIED infections in LVAD recipients. A retrospective study of 215 LVAD recipients with a CIED showed that 6 patients (2.8%) subsequently developed infections: 3 had lead endocarditis, and 3 were diagnosed with pocket infection. Pocket infections occured after generator change, whereas the patients who developed endocarditis had prior LVAD infection. Infecting organisms included *Pseudomonas aeruginosa*, coagulase-negative staphylococci, methicillin-resistant *Staphylococcus aureus*, and a Gram-positive bacillus; 2 patients had culture-negative infections. Despite complete CIED and lead extraction and short-term antibiotic therapy with continued suppressive antibiotic therapy, the reported mortality rates for LVAD-associated CEID infections have ranged from 17% to 83% at 15 months after presentation.[107,108]

Both retrospective and prospective registry data sets for lead extraction show a major procedural complication rate as high as 2.5% and a procedure-related mortality rate as low as 0.5%.[109–111] Unfortunately, the current registry publications do not separately report data for the population of patients with an LVAD. Therefore, these published complication rates may not fully capture the degree of risk associated with lead extraction in patients with an LVAD because the population of patients included in the extraction registries had fewer overall comorbidities then the typical LVAD population. Thus, the risk estimates for patients with an LVAD undergoing extraction are likely higher.

Without specific data, lead extraction management decisions must be extrapolated from the current trans-

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venous lead extraction expert consensus statement.[112] Lead extraction after LVAD implantation may be indicated in, but not limited to, the following select situations: device infection, recurrent VAs attributable to transvenous leads, mechanical or design failures of transvenous leads that pose a near-term threat to the patient, or interference in LVAD function by the defibrillation system. In the current expert consensus statement, patients with a life expectancy of <1 year are not recommended for lead extraction because of the risk for procedural complications (Class III recommendation).[112] In patients who underwent LVAD implantation as BTT, lead extraction may be considered in situations of generator and lead infections given that transplantation is a goal in these patients and in-dwelling infections are life-threatening in the setting of immunosuppressive therapy after transplantation. This situation was given a Class I indication for lead extraction in the 2017 Heart Rhythm Society expert consensus statement on CIED lead management and extraction.[112]

Programming of ICD and CRT-D Devices After LVAD Implantation

Programming After LVAD to Reduce Shocks

As noted, many patients with a ventricular assist device tolerate sustained VT, VF, or even asystole, with published reports demonstrating clinically stable presentation with continuous VT/VF for >24 hours.[113–116] There is, however, concern about a reduction in pump flow and cardiac output during sustained VAs,[55,56,117] as well as potential adverse effects on RV function or thrombosis in a fibrillating RV.[59] ICD shocks are common, and patients with an LVAD are frequently admitted to the hospital for management.[40,41,43–46] Given generally excellent hemodynamic tolerance to sustained VAs, most patients with an LVAD are awake at the time of an ICD shock. ICD shocks have deleterious consequences, both physically and psychologically.[82,118,119] Unfortunately, data on the optimal programming of CIEDs in patients with an LVAD are limited. Richardson et al,[80] in a single-center prospective randomized trial of 83 patients, compared an ultraconservative ICD programming strategy (maximal allowable intervals to detection in the VF and VT zone with use of ATP) with standard ICD programming. The primary outcome was time to first ICD shock. There was no significant difference between groups in time to first ICD shock or total ICD shocks. No harmful effects on mortality or hospitalization were seen with extending VT/VF zones to the maximum allowable detection times.[80] Thus, an ultraconservative programming strategy with high rate cutoff limits for tachycardia therapies, prolonged tachycardia detection programming, and aggressive use of ATP algorithms, as supported by clinical trial evidence in the non-LVAD population, also should be used in the LVAD population.[120–123] We suggest a high rate cutoff VF zone (240–250 beats per minute) with the longest programmable detection time available on the device. A second zone can be added for patients at risk of or with a known history of VA with the highest detection cutoff allowed by the device unless the VA is known to result in hemodynamic instability. In this zone, aggressive and multiple runs of ATP can prevent or significantly delay the delivery of an ICD shock. Alternatively, any zone other than the VF zone can be programmed as an ATP-only zone for patients with recurrent VAs that are amenable to ATP. In current devices, US Food and Drug Administration regulations do not allow ATP-only programing in the VF zone. On the other hand, tachycardia monitor zone–only programming could lead to failure to treat sustained slow VT. In patients with severe RV dysfunction or pulmonary hypertension, this could worsen HF and systemic perfusion. In patients who have hemodynamically significant slow VT or in whom there are concerns about hemodynamic or thrombotic complications, ablation may be the most advantageous strategy. Similar attention to a reduction in inappropriate shocks for supraventricular tachycardia, AF, or atrial flutter should be given with the use of atrial diagnostics, QRS morphology match, and tachycardia discriminators. Supraventricular tachycardia (sustained rate duration) timeout should be turned off. Atrioventricular nodal ablation can be used to prevent inappropriate shocks from medically refractory supraventricular arrhythmias with rapid ventricular rates.

Programming of ICD tachycardia detection and therapies after LVAD implantation is restricted, at present, by programming limits set in place by the original US Food and Drug Administration approvals of ICD algorithms (Table 1). Better algorithms for programming long detection times are needed in patients with an LVAD with an ICD.

Programming to Conserve Battery: Turning Off the LV Lead

The decision of whether to continue CRT therapy after LVAD implantation is complex. LV pacing has been shown to greatly shorten time to elective replacement indicator.[124] Generator replacement of pacemaker or

Table 1. Maximal Allowed Time to VA Detection in Current-Generation ICDs

Manufacturer	VF Zone Detection	VT Zone Detection
Boston Scientific	15 s to detection	60 s to detection
Medtronic	120/160 beats (32.4 s) to detect; redetect 30/40 beats	100 intervals (33 s) to detect; redetect 52 intervals
St. Jude Medical (Abbott)	100 intervals to detection (25 s)	100 intervals (33 s) to detection

ICD indicates implantable cardioverter-defibrillator; VA, ventricular arrhythmia; VF, ventricular fibrillation; and VT, ventricular tachycardia.

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ICD has a major complication rate of 4% in the REPLACE registry (Implantable Cardiac Pulse Generator Replacement Registry), and in the LVAD population, this is further complicated by uninterrupted anticoagulation and acquired von Willebrand disorder, raising the risk for significant pocket hematomas, which can promote infection.[125,126] Available studies show no conclusive survival or hospitalization benefit with continued CRT during LVAD support and show conflicting information on freedom from VAs.[7,17,80,81] Recent multicenter data on 488 patients with a CF-LVAD showed that continued CRT, compared with ICD only, after LVAD implantation resulted in a significantly higher need for pulse generator changes.[81] Hence, the decision to continue LV pacing may be guided by the LV pacing threshold, LV lead position, and any potential hemodynamic or arrhythmic benefits for that individual patient. In addition, the current battery status should be taken into account, particularly when the patient is listed for heart transplantation, in efforts to avoid an unnecessary generator replacement procedure.[127] The consensus from the writing group is that in patients with an existing CRT-D device who receive a CF-LVAD, careful consideration should be given to whether to deactivate the LV lead after ventricular assist device implantation. In addition, programming the device to conserve battery and to avoid unnecessary pulse generator replacement is advised. In patients with primary prevention ICDs and no sustained VA noted after long-term LVAD support, the benefit of generator replacement at elective replacement indicator should be balanced against the procedural risks involved.

Turning Off ICDs in LVADs

Close collaboration between the LVAD team and the electrophysiology team is critical for CIED and arrhythmia management in patients with an LVAD. This is especially important in the first 30 days after the LVAD implantation because >50% of arrhythmias and ICD therapies occur during this period.[40,41,43–46] The vast majority of patients with a CF-LVAD are fully conscious when they receive ICD shocks. Painful, recurrent ICD shocks can have psychological consequences and negatively affect quality of life.[128,129] Thus, even apart from end-of-life scenarios, certain patients with an LVAD may request to have their ICD therapies programmed off to stop painful ICD therapies. Although available data do not clearly show a significant impact of the ICD on survival in the CF-LVAD population,[15,78] randomized studies are lacking. Hence, the decision to turn off ICD therapies should be done on a case-by-case basis and involve shared decision making with the patient and family.

End-of-life defibrillation deactivation should be discussed in an anticipatory manner in the pre-evaluation LVAD period with the patient and family.[18] Moreover, these conversations should be ongoing because goals and prior significant decisions may change over time and in relationship to the changes in cardiac health/other comorbidities.

MANAGEMENT OF ARRHYTHMIAS IN THE PATIENT WITH AN LVAD

Atrial Arrhythmias

Although medical management of AAs is well described in the non-LVAD population,[130] data on how to best manage AAs after LVAD implantation are lacking. Specifically, the impact of AAs on either symptoms or hemodynamics in the population of patients with a CF-LVAD is unclear. Therefore, determining the benefit of any particular treatment is challenging. In this setting, strategies for medical management of AAs among patients with an LVAD are based on either extrapolation of pre-established guidelines in non-LVAD populations or small retrospective or single-center reports.

Anticoagulation is required (in the absence of contraindications) for patients with LVADs to reduce the risk of pump thrombus and thromboembolic events,[32] and the presence of AF typically does not influence the international normalized ratio target in these patients. Rate control is an important management strategy for patients with AF.[130] Although it remains unproven whether the reverse remodeling effects of β-blockers in patients with HF with reduced ejection fraction (HFrEF)[131–134] extend to those with LVADs, 1 of the 3 β-blockers approved for HFrEF (carvedilol, bisoprolol, or metoprolol succinate)[118] is generally continued in the absence of any clear contraindication (eg, hypotension, orthostasis, severe RV dysfunction). β-Blockers can be used to achieve rate control in patients with an LVAD with AF and are perhaps the most common agent used for this purpose. Nondihydropyridine calcium channel blockers should be used cautiously in patients with HFrEF because of their negative inotropic effects, and the role of these agents in LVAD recipients remains unclear. Digoxin is frequently used in patients with HFrEF as an adjunct to goal-directed medical therapy to reduce the rate of HF-related hospitalizations[119] and, in this setting, is frequently incorporated into medical management strategies of patients with HFrEF after LVAD implantation.[135] The combination of β-blockers and digoxin has previously been shown to be an effective strategy for achieving AF rate control at rest and during exercise[136,137] and can be considered in patients with an LVAD with AF. The ideal heart rate or rate control strategy in LVAD recipients is not clear and may be different from that in the non-LVAD population given the myriad differences in physiology.

In situations when a patient with an LVAD is unable to tolerate AF, as a result of a decline in either symp-

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toms or functional capacity[66] or hemodynamic instability, it may be necessary to restore and maintain sinus rhythm. There is a paucity of data available to guide strategies for rhythm control in LVAD recipients, and further studies are clearly needed in this regard. Thus, management typically follows what has been recommended by guidelines for AF in patients with HFrEF.[131]

Although data on the efficacy of amiodarone as a rhythm control strategy for patients with an LVAD have been limited to single-center experiences or retrospective analyses of either AA or VA management, 40% of patients with an LVAD are prescribed amiodarone 3 to 6 months after device implantation. We found no reports detailing the efficacy for AF specifically in the population of patients with an LVAD.[11,66,138] Dofetilide in an effective drug for rhythm control of AF, has a neutral effect on mortality among patients with HF,[131,139] and is a reasonable option for rhythm control in this population. Sotalol is another option and is generally well tolerated in patients with structural heart disease but should be used with caution because of negative inotropic effects.[131]

Ventricular Arrhythmias

Despite a high incidence of VAs in patients with LVADs, data on how to best manage VAs in this population are limited to small observational studies and case reports.[10,40,42] Therefore, current practices are generally based on extrapolation of studies of antiarrhythmic drugs for managing VAs in patients with structural heart disease and ICDs.[140]

In the setting of documented VAs (secondary prevention), no antiarrhythmic drug has been shown to improve survival better than ICD therapy.[141] Antiarrhythmic therapy is often limited by variable efficacy, proarrhythmic effects, and adverse effects from long-term use.[130] However, ICD shocks, both appropriate and inappropriate, have been associated with significant mortality and morbidity.[82] Therefore, antiarrhythmic drug therapy is often used in ICD recipients with VA to improve symptoms, to reduce ICD therapies, and, in the case of LVADs, to prevent hemodynamic instability associated with VAs. However, the potential benefits of drugs are even more uncertain in patients with an LVAD because most sustained VAs are very well tolerated.

Most patients who receive an LVAD are likely already on an optimal dose of β-blocker therapy unless not tolerated or contraindicated. However, in patients with documented VAs (secondary prevention), β-blockers have not been shown to significantly improve outcomes.[142,143] In a retrospective study of 42 patients with a pulsatile LVAD, Refaat and colleagues[40] reported a strong association between β-blocker nonuse and the risk of subsequent VAs (odds ratio, 7.04 [*P*=0.001]). Conversely, in a prospective study of 23 patients with a HeartMate 2 CF-LVAD, no predictors of VA were identified, including postoperative therapy with β-blockers.[42] The observational nature, small sample size, and difference in LVAD types likely explain the divergent findings in these studies. In patients who develop sustained VAs despite β-blockade, additional treatment options are often necessary.

The randomized OPTIC trial (Optimal Pharmacological Therapy in Cardioverter Defibrillator Patients) showed that amiodarone plus a β-blocker and sotalol significantly reduced the rate of recurrent VT in (non-LVAD) ICD recipients compared with β-blockers alone. The combination of amiodarone plus β-blocker was more effective than sotalol but at the expense of increased risk of drug-related adverse effects.[142] A pooled quantitative estimate of the benefit of class III antiarrhythmics (amiodarone, sotalol, azimilide, and celivarone) on survival and ICD shock reduction in 2268 patients reported a 34% reduction in appropriate ICD interventions with antiarrhythmics compared with control medical therapy, which did not translate into a significant effect on all-cause mortality. Notably, the benefit observed was almost all due to amiodarone and could not be confirmed for other drugs.[144] Amiodarone has also been investigated in patients with LVADs in smaller studies. Raasch et al[10] reported a 60% arrhythmia-free survival in 15 patients who had amiodarone initiated after the occurrence of VAs (secondary prevention). Gopinathannair et al,[81] in a multicenter CF-LVAD cohort (n=488) showed that baseline amiodarone use was independently associated with increased mortality (HR, 1.77 [95% CI, 1.1–2.8]; *P*=0.018), although these findings could reflect a sicker cardiac substrate. Thus, the benefits of amiodarone must be tempered against the potential for organ toxicity, side effects, and drug interactions, especially with warfarin. Thus, close monitoring is required, and drug discontinuation because of side effects is expected. Other agents that can be used for VA suppression include mexiletine, dofetilide, azimilide, celivarone, and ranolazine.[145–148] The only evidence for mexiletine in patients with an LVAD comes from the study by Raasch et al[10] in which mexiletine was added to amiodarone in 4 patients and was effective in only 1 case.

Intravenous amiodarone and sodium channel–blocking agents such as lidocaine and procainamide remain the preferred drug regimen in the short-term setting. More data are sorely needed to better understand the role of targeted antiarrhythmic therapy in LVAD recipients who develop VAs. Given the lack of conclusive evidence that either antiarrhythmic drugs or ICDs improve outcomes in LVAD recipients, careful assessment of symptoms and hemodynamic changes associated with VAs and balancing those against the side effects and potential drug interactions of the specific antiar-

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rhythmic agent appears to be the best strategy in this population.

Catheter Ablation in LVAD Recipients

Role of Catheter Ablation in AAs

There is a paucity of information on the safety and efficacy of catheter ablation in patients with an LVAD with AAs. Two reports have described the impact of ablation therapy on patients with an LVAD with atrial flutter and AF. Maury et al[149] described 1 patient with ablation of both typical and atypical atrial flutter resistant to amiodarone and resulting in hemodynamic compromise. Hottigoudar et al[70] reported cavotricuspid isthmus ablation in a series of 8 patients with HeartMate II LVADs and typical atrial flutter. Seven of 8 patients had new atrial flutter after LVAD implantation, and all had features of right-sided HF. Seven patients underwent cavotricuspid isthmus ablation with restoration of sinus rhythm and resolution of their symptoms. After a mean follow-up of 9 months, the patients remained free of atrial flutter.

It should be noted that the above studies reported only patients in whom AAs had a significant impact on their symptoms and hemodynamic status. AAs in patients supported with an LVAD are not always symptomatic, discouraging most operators from subjecting the patient to the risks of an ablation procedure. This might explain the small number of studies reported. In patients with an LVAD, retrospective studies showed that AF was associated with decreased functional status, decreased quality of life, and increased risk of HF hospitalizations, but not with increased mortality.[66,150] However, no studies have reported the effect of AF ablation on these outcomes in patients with an LVAD.

In the general population, long-term suppression of typical atrial flutter is difficult to achieve with antiarrhythmic therapy, and catheter ablation is now considered a first-line therapy with a high success rate (>95%) and low complication rate.[151] Accumulating evidence suggests that patients with HF and drug-intolerant or drug-refractory AF have improved outcomes with ablation compared with medical therapy.[152,153] However, because the majority of the cardiac output in patients with an LVAD is provided by the mechanical pump, it is unknown whether restoration of sinus rhythm significantly affects the hemodynamic and functional status of these patients. In addition, the success rate of AF ablation in this sicker patient population is entirely unknown.

From a technical standpoint, the distortion of cardiac geometry by the LVAD may interfere with the anatomic representation of the cardiac structures on standard fluoroscopic views. The ablation procedure should be done without interruption of anticoagulation given the increased risk of thromboembolism in patients with an LVAD. Fortunately, the atrial location of mapping catheters makes electromagnetic interference from the LVAD less likely.

In summary, ablation therapy should be considered as a first-line therapy for typical atrial flutter in patients with an LVAD if there is a clear hemodynamic and functional compromise because of atrial flutter. It is reasonable to consider catheter ablation for drug-resistant or drug-intolerant AF with a clear hemodynamic compromise in patients with an LVAD. Although recent studies support the role of AF ablation in patients with HF, no data on the efficacy and safety of AF ablation in patients with an LVAD are available.

Role of Catheter Ablation in VAs

Although VAs are usually well tolerated in patients with an LVAD, they can be hemodynamically significant and can cause symptoms, ICD shocks, and RV failure.[36,42,50] In patients without LVAD support, catheter ablation is an established treatment option for patients with VAs when antiarrhythmic medications are ineffective, not tolerated, or not desired by the patient.[79] Catheter ablation for VAs in LVAD recipients has been described in 8 retrospective cohort studies and case series, including a total of 101 patients with recurrent or intractable drug-refractory VA resulting in ICD shocks or hemodynamic compromise (Table 2).[12,13,50,154–158] Most patients had a CF-LVAD, and 60% had ischemic cardiomyopathy. Twenty-seven percent of patients had VT that was related to the LVAD cannula, from either mechanical trauma of the endocardium or a re-entry circuit between the cannula and preexisting myocardial scar; the rest, and the majority, were related to preexisting cardiomyopathy substrate. The VT mechanism was macroreentry in the vast majority, followed by microreentrant or focal and bundle-branch reentry.[12,50,154,158]

The short-term procedural success ranged between 77% and 86%.[12,154] Follow-up was variable between the studies, and VA recurrence rate during follow-up ranged from 15% to 86%. The marked variability in recurrence rates may be explained by slightly different definitions of VA recurrence and the different thresholds to pursue ablation in this population. Moreover, the studies showed a significantly decreased VA burden even when the recurrence rates were higher, often enough to stabilize the patient to undergo a heart transplantation or to be discharged from the hospital. Moss et al,[158] in their study on 21 patients with a CF-LVAD, observed for the first time that patients who had freedom from recurrent VA after ablation had better survival at 1 year compared with those with recurrence (67% vs 29%; P=0.049). Complications of the procedure included cerebrovascular accident (2.6%), cardiogenic shock (1.3%), and vascular access–related complications (2.6%). Care should be taken to balance the volume status during the ablation procedure be-

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Table 2. Summary of Available Data on Outcomes of VT Ablation in LVAD Recipients

	Patients, n	ICM, n (%)	CF- LVAD, n (%)	Follow-Up, mo	VTs (average/patient), n	Recurrence, n (%)	Epicardial Ablation, n
Dandamudi et al[154] (2007)	3	2 (66)	0 (0)	4–12	6 (2)	1 (33)	0
Hottigoudar et al[13] (2011)	3	1 (33)	3	2–10	15 (5)	2 (66)	0
Cantillon et al[50] (2012)	21	12 (57)	NR	4.4±3.3	28 (1.3)	7 (33)	0
Herweg et al[155] (2012)	6	4 (66)	4 (66)	7.5±6.9	14 (2.3)	2 (33)	0
Garan et al[156] (2014)	7	5 (71)	7 (100)	5±3.6	19 (2.7)	6 (86)	1
Sacher et al[12] (2015)	34	21 (62)	34 (100)	25±15	110 (3.2)	5 (15)	0
Snipelisky et al[157] (2017)	6	2 (33)	6 (100)	6	18 (3)	5 (83)	1
Moss et al[158] (2017)	21	14 (66)	21 (100)	9	2.5 (2–4.5) per patient	7 (33)	0

CF-LVAD indicates continuous-flow left ventricular assist device; ICM, ischemic cardiomyopathy; LVAD, left ventricular assist device; NR, not reported; and VT, ventricular tachycardia

cause volume overload can still cause HF decompensation. Similarly, inducing VT for prolonged periods of time can worsen RV function and consequently LVAD function. Concerns have arisen recently about early and late pump thrombosis in patients who undergo VT ablation.[158] This association remains unclear and requires prospective evaluation in a larger study. No deaths were reported during an ablation procedure. Overall, 38% of the patients with ablation underwent heart transplantation, and 36% died during the follow-up period. The majority of deaths were nonarrhythmic.

There are several procedural aspects to consider during VT ablation in LVAD recipients. Given the low peripheral pulsatility with CF-LVADs, the automatic sphygmomanometer might not capture the blood pressure adequately, and invasive hemodynamic monitoring is usually needed. LVAD flows should be closely monitored during the procedure. Similarly, vascular access might require the use of ultrasound. The transseptal approach with a deflectable sheath is preferred. The retrograde approach might be challenging because there is little or no flow through the aortic valve, which can also be oversewn in some patients. The LVAD pump speed can be reduced to allow the aortic valve to open further for catheter entry. Similarly, reducing pump speed might improve catheter maneuverability inside the LV if the LV volume is significantly decreased by the LVAD. There is a theoretical possibility of catheter entrapment in the LVAD cannula, but the risk is very low. In fact, the catheter can be placed accidentally or purposefully in the proximal portion of the cannula to mark it on the mapping system with no incident as long as the catheter is not placed deep in the cannula where the rotating impeller is.[12] More care should be taken with centrifugal LVAD pumps in which the inflow cannula accesses the rotating impeller directly with no turns, as with HVAD and HeartMate 3. Intracardiac echocardiography can be very useful because distortion in LV geometry from LVAD placement can alter standard fluoroscopic views.[13]

The HeartMate 2 and HVAD do not usually interfere with magnet-based mapping systems, but they can occasionally limit the visualization of the catheter and mapping in the inferior or septal apical segments around the cannula and facing the turbine.[12,154] HeartMate 3, however, presents additional challenges. Unlike other CF-LVADs, the HeartMate 3 causes high-frequency noise on the surface ECG that makes morphology discrimination challenging; noise seems to disappear with higher revolutions per minute during the "pulse" delivery by the device every 2 seconds (Figure 3). Adjusting the low-pass filter can sometimes help with the quality of the ECG but should be balanced against losing some fractionation or even amplitude in the QRS signal, which can also affect discrimination. Compatibility of HeartMate 3 with magnetic mapping and navigation needs further study.

In patients with an LVAD, both adhesions from the LVAD implantation or other prior cardiac surgery and the location of the LVAD in the chest make the subxiphoid puncture technique for epicardial access not feasible. However, surgical epicardial access with limited thoracotomy can be used in patients with LVADs to ablate epicardial VTs that are hemodynamically significant.[156,157,159]

Given the challenges of VT ablation after LVAD implantation, surgical ablation of patients with recurrent preoperative VT is sometimes considered during the implantation of the LVAD because it provides exposure of the entire epicardium and some endocardium through the ventriculotomy for the inflow cannula. Three studies have reported epicardial alone or both endocardial and epicardial ablation of VT during LVAD implantation.[160–162] The first report described an empirical surgical cryoablation during LVAD implantation based on prior electrophysiology study and scar mapping or electrocardiographic morphology of the VT.[160] Both endocardial cryoablation and epicardial cryoablation were performed, connecting regions of scar to anatomic barriers in 7 patients. Outcomes were subsequently

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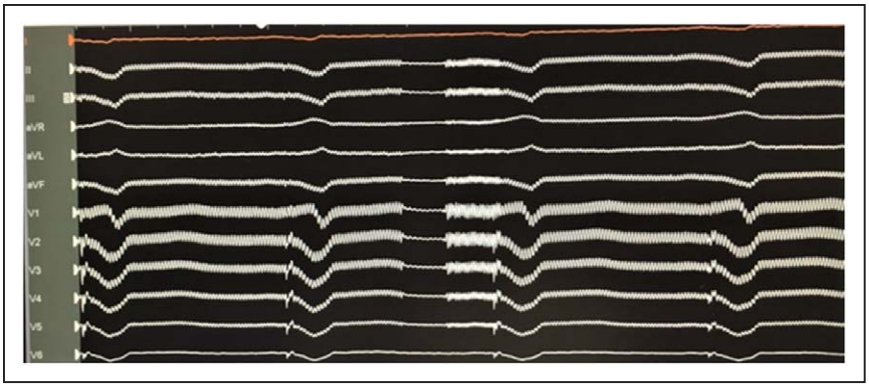

Figure 3. High-frequency surface electrocardiographic noise that typically is seen in the presence of a HeartMate 3 left ventricular assist device.
This noise can make morphology discrimination challenging. Noise seems to disappear with higher revolutions per minute during the pulse delivery by the device every 2 seconds. Sweep speed is100 mm/s.

compared with another 7 patients with an LVAD who did not undergo intraoperative ablation. None of the patients undergoing ablation had recurrent VTs postoperatively compared with 4 patients in the control group, and the ablation group had a shorter intensive care unit stay and hospital length of stay. No significant complications were reported. Another study reported open chest, epicardial only, radiofrequency ablation in 5 patients who had failed a preoperative endocardial ablation (4 of 5 patients) or had electrocardiographic features of epicardial VT.[161] Short-term procedural success was achieved in 3 of 5 patients, with VT burden eliminated or significantly reduced in all patients. One patient had mediastinal bleeding after ablation. During a mean follow-up of 363 days, 4 of 5 patients died, all of nonarrhythmic causes. The third study reported 2 patients who underwent endocardial and epicardial cryoablation during LVAD implantation.[162] Both ablations were successful but were complicated by LVAD thrombosis requiring LVAD exchange. This report raised concerns about the thrombotic risk with perioperative endocardial ablation. However, this complication was not observed in the previous study.[160]

There are technical issues to consider during surgical VT ablation either during or after implantation of the LVAD. Care needs to be taken in patients with previous coronary bypass surgery to avoid bypass grafts and graft touchdowns. Patients may require selective lung ventilation because the left lung might need to be deflated for optimal exposure of the anterior and lateral walls of the heart. One must rely on the limb leads only during mapping because the precordial leads of the ECG are not reliable in determining the location of the VT or comparing the induced and clinical VTs because of the open chest exposure. Mapping through an apical incision limits the ability to map the entire chamber, and the lack of electroanatomic correlation can be challenging. In addition, the metal retractors for the open chest can interfere with the electroanatomic mapping systems, which sometimes prohibits mapping in certain areas of the heart or prohibits the use of such systems altogether. Although closed irrigated ablation catheters were used the most in reported studies, surgical radiofrequency or cryoablation tools are more appropriate to deliver higher-quality lesions.

In summary, VT ablation should be considered for patients with an LVAD and recurrent VT resulting in hemodynamic compromise and ICD shocks. There currently is no strong evidence that VT ablation changes mortality in this patient population; larger-scale studies are needed to explore this further. However, ablation can be beneficial in suppressing or decreasing the VT burden, reducing the length of hospital stay, improving quality of life, and stabilizing patients in order to be bridged to transplantation or discharged from the hospital in stable condition. Surgical epicardial ablation can be considered in patients with evidence of epicardial arrhythmias who fail endocardial ablation and whose VT is still of significant hemodynamic impact. The appropriate timing of VT ablation in patients with advanced HF in need of an LVAD remains unclear. The efficacy and safety of surgical endocardial and epicardial ablation during LVAD implantation are still unknown, but early positive experience suggests that further evaluation, as a therapy to decrease VT burden and improve outcomes postoperatively, is warranted.

INTERDISCIPLINARY COLLABORATION IN ARRHYTHMIA MANAGEMENT IN PATIENTS WITH AN LVAD AND FAMILIES/CAREGIVERS

A multidisciplinary team–based approach to care is imperative for an LVAD recipient. Close collaboration between the LVAD team, the electrophysiology team, the patient with an LVAD, and their families/caregivers is critical for shared decision making, optimal CIED management, and arrhythmia care in patients with an LVAD.[163–165] This area is especially important given the rapid growth of individuals who are living long term with an LVAD as DT. The DECIDE-LVAD randomized trial (Trial of a Decision Support Intervention for Patients and Caregivers Offered Destination Therapy Heart Assist Device) examined the effectiveness of supporting

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Table 3. Summary of the Writing Group's Consensus View on the Suggestions/Considerations/Implications for Clinical Practice Based on the Evidence Presented in This Scientific Statement

1	Available observational data show no survival benefit for ICD therapy in patients with CF-LVADs. There is no randomized controlled trial evidence to guide these recommendations.
2	Patients who do not have an ICD before LVAD implantation may be considered for ICD implantation on a case-by-case basis, and shared decision making with the patient and family is important in terms of the risks and benefits of ICD implantation. Similarly, in patients with primary prevention ICDs and no sustained VAs noted after long-term LVAD support, the benefit of generator replacement at elective replacement indicator should be balanced against the procedural risks involved.
3	Close attention to programming CIED bradycardia and tachycardia parameters to conserve battery and to avoid unnecessary pulse generator replacement is advised. In patients with an existing CRT-D device who receive a CF-LVAD, consideration can be given to programming LV pacing off after LVAD implantation in the absence of any hemodynamic intolerance or increased arrhythmogenicity.
4	Because sustained VAs in patients with an LVAD are often well tolerated and given the adverse consequences of recurrent and painful ICD shocks, a conservative programming strategy should be used with the aim of minimizing ICD shocks. We suggest a high-rate cutoff VF zone (240–250 bpm) with the longest programmable detection time available on the device. A second zone can be added for patients at risk of or with a known history of VAs with the highest detection cutoff allowed by the device unless the tachycardia is known to result in hemodynamic instability. In this zone, aggressive and multiple runs of ATP can prevent or significantly delay the delivery of an ICD shock. Alternatively, any zone other than the VF zone can be programmed as an ATP-only zone for patients with recurrent VAs that are amenable to ATP. If ATP is unsuccessful at terminating a VT episode, elective cardioversion or defibrillation under sedation is advised.
5	Because the risk of sudden arrhythmic death is low, even apart from end-of-life scenarios, certain patients with an LVAD may prefer to have their ICD therapies programmed off to minimize painful ICD shocks. Hence, the decision to turn off ICD therapies for any indication should be made on a case-by-case basis involving shared decision making with the patient and family. An alternative option would be to give the patient a magnet to disable ICD therapies when needed.
6	In the past, interaction between the CF-LVAD operating frequency and the telemetry frequency of specific ICD models resulted in telemetry dropout and failure to interrogate. This is not a concern with modern CIEDs.
7	Implantation of an LVAD can result in alterations of lead parameters. CIED interrogation immediately after LVAD implantation is recommended. Given uncertainty about survival benefit of ICD therapies in patients with CF-LVADs, routine defibrillation threshold testing is not recommended after LVAD implantation but can be considered in select patients with high VA burden with hemodynamic instability or failed ICD therapies.
8	Multicenter observational data show no survival advantage for CRT in patients with a CF-LVAD. Data on whether continued CRT-D after CF-LVAD reduces VT and ICD shocks are conflicting.
9	AAs and VAs are commonly seen in patients with a CF-LVAD and are mostly well tolerated, and their impact on clinical outcomes is not well defined.
10	AAs with rapid ventricular response compromising CF-LVAD flows and performance should undergo electric or chemical cardioversion, and rhythm control should be considered in these patients.
11	Limited information is available to guide antiarrhythmic drug use for rhythm control for AAs and VAs in LVAD recipients, and current guideline recommendations[79,131] to treat AAs and VAs in the non-LVAD population can be followed in these patients.
12	Ablation therapy should be considered as a first-line therapy for typical atrial flutter in patients with an LVAD if there is a clear hemodynamic and functional compromise from the atrial flutter.
13.	Recurrent VAs in a patient with a CF-LVAD should prompt evaluation to rule out a suction event or other reversible causes such as electrolyte disturbances and drug proarrhythmia.
14	The provider should consider turning off ICD therapies in patients with biventricular support who are in persistent VT or VF with stable VAD flows.
15	VT ablation should be considered in patients with an LVAD with recurrent, drug-resistant VAs resulting in hemodynamic compromise or recurrent ICD shocks and should be performed by an electrophysiologist with knowledge and expertise in treating patients with an LVAD.
16	For patients with significant VAs before LVAD implantation, intraoperative VT ablation during LVAD implantation may be effective at reducing postoperative VAs. This should be performed at specialized centers.
17	Given the complexity of the LVAD population and the specialized nature of management resulting from manifest differences in underlying physiology, it is reasonable to consider a paradigm in which patients with a CF-LVAD with CIEDs are followed up in the LVAD implanting center by a multidisciplinary team consisting of the LVAD team, the electrophysiology team, and advanced practice nurses who are experienced in specific CIED- and arrhythmia-related issues in LVAD recipients.

AA indicates atrial arrhythmia; ATP, antitachycardia pacing; CF-LVAD, continuous-flow left ventricular assist device; CIED, cardiac implantable electronic device; CRT, cardiac resynchronization therapy; CRT-D, cardiac resynchronization therapy–defibrillator; ICD, implantable cardioverter-defibrillator; LV, left ventricular; LVAD, left ventricular assist device; VA, ventricular arrhythmia; VAD, ventricular assist device; VF, ventricular fibrillation; and VT, ventricular tachycardia.

shared decision making for patients offered a DT LVAD across 6 US sites. After random variation of time in usual care, sites were transitioned to an intervention that integrated decision aids and clinician training into standard of care processes. The results demonstrated significantly better knowledge and higher concordance between the patient's stated values and patient-reported treatment choices.[166]

Given the complexity of these patients and the specialized nature of clinical decisions and management resulting from manifest differences in underlying physiology, it is reasonable to consider a paradigm in which patients with a CF-LVAD with CIEDs are followed up in the LVAD implanting center by a multidisciplinary team consisting of the LVAD team, the electrophysiology team, and advanced practice nurses who are experienced in specific CIED- and arrhythmia-related issues and can provide the necessary education and support for LVAD recipients and their caregivers.

IMPLICATIONS FOR CLINICAL PRACTICE

The writing committee's consensus view on the suggestions/considerations/implications for clinical practice,

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Table 4. Limitations of Existing Studies Evaluating CIED and Arrhythmia Management and Recommendations for Future Research in This Field in Patients With an LVAD

Limitations of existing studies
There is a lack of large randomized studies to assess the impact of CIED therapy in LVAD recipients. Most studies are retrospective; many are single center and suffer from small sample size and inherent biases.
There is a lack of prospective studies available to guide antiarrhythmic or ablation therapy for AAs and VAs in LVAD recipients.
Future directions
Randomized trials with long-term follow-up are needed to better understand the utility of either continued ICD or CRT therapy after LVAD implantation. It is important to better understand whether ICD or CRT therapies need to be continued after LVAD implantation and whether new ICD implantations are useful after LVAD implantation.
In the absence of randomized data, multicenter studies and prospective registry data are necessary to provide a higher level of evidence to inform guidelines.
Better options for programming long detection times in ICDs in LVAD recipients are needed. Similarly, whether any specific CRT programming has value in patients with an LVAD needs to be investigated in future clinical trials.
Is there a role for CRT in bridge-to-recovery patients? Does biventricular pacing or LV pacing affect functional capacity and quality of life? If so, what is optimal programming?
Whether early or aggressive management of AAs improves outcomes in LVAD recipients needs further study.
Targeted studies on antiarrhythmic therapy for AAs and VAs in LVAD recipients are needed.
Studies to better understand the relationship between sustained AAs or VAs and right-sided heart failure in LVAD patients are needed.
Studies to better evaluate clinical and life decisions made by patients, caregivers, and providers and their impact on quality of life and outcomes are warranted.

AA indicates atrial arrhythmia; CIED, cardiac implantable electronic device; CRT, cardiac resynchronization therapy; ICD, implantable cardioverter-defibrillator; LV, left ventricular; LVAD, left ventricular assist device; and VA, ventricular arrhythmia.

based on the evidence presented in this scientific statement, is summarized in Table 3. In addition, the writing committee has identified the important, but not inclusive, limitations of existing studies and have outlined our recommendations for future research in Table 4.

CONCLUSIONS

LVADs are increasingly used as both BTT and DT, with the vast majority of recipients having a CIED (ICD or CRT-D) and a high incidence and prevalence of AAs and VAs. It is important for both the LVAD team and the electrophysiology team to have a working knowledge of the complexities involved in managing CIEDs and arrhythmias in the patient with an LVAD. This document details research that has been done in this burgeoning field and clearly acknowledges the tremendous gaps in knowledge to guide management. Most important, there is a clear need for randomized trials and longitudinal registry data to address these relevant clinical questions. The support of entities such as the American Heart Association is critical for facilitating additional research to better understand and appropriately manage device therapy and arrhythmia management in this complex, unique, and growing group of patients.

ARTICLE INFORMATION

The American Heart Association makes every effort to avoid any actual or potential conflicts of interest that may arise as a result of an outside relationship or a personal, professional, or business interest of a member of the writing panel. Specifically, all members of the writing group are required to complete and submit a Disclosure Questionnaire showing all such relationships that might be perceived as real or potential conflicts of interest.

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Disclosures

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This table represents the relationships of writing group members that may be perceived as actual or reasonably perceived conflicts of interest as reported on the Disclosure Questionnaire, which all members of the writing group are required to complete and submit. A relationship is considered to be "significant" if (a) the person receives $10 000 or more during any 12-month period, or 5% or more of the person's gross income; or (b) the person owns 5% or more of the voting stock or share of the entity or owns $10 000 or more of the fair market value of the entity. A relationship is considered to be "modest" if it is less than "significant" under the preceding definition.

*Modest.

†Significant.

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*Modest.

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