Despite advances in medical therapy, heart failure remains one of the major causes of hospitalizations and deaths in the United States. Approximately 5.7 million patients have heart failure, and it is the direct cause of death for 57,000 individuals annually. Although the combination of optimal medical therapy, implantable cardioverter-defibrillators (ICDs), and cardiac resynchronization therapy has reduced mortality rates, an estimated 50% of patients with heart failure still die within 5 years of diagnosis. Heart transplant is often the best therapeutic option for patients with end-stage heart failure; however, there has been a stable plateau of ≈2200 transplants/year in the United States due largely to limitations in organ availability. For patients who are facing unfavorably long wait times for heart transplantation, left ventricular assist devices (LVADs) have become a lifesaving option as a bridge to transplant. Currently, one quarter to one third of all heart transplant recipients are bridged with mechanical circulatory support before transplantation. Much of this support is in the form of permanent LVADs—surgically implanted mechanical assist devices that unload the left ventricle and can function in ambulatory patients (Figure 1). The use of permanent LVADs as destination therapy has increased dramatically, with evidence that they benefit patients with end-stage heart failure, despite noncandidacy for heart transplantation.

Since the seminal Randomized Evaluation of Mechanical Assistance for the Treatment of Congestive Heart Failure destination therapy trial in 2001, ≈1578 destination therapy LVADs have been implanted, with implant rates increasing rapidly. Development of LVADs dates to 1969 when the world’s first total artificial heart was implanted by Dr. Cooley to support a 47-year-old patient. Since then, there has been remarkable advancement in LVAD design and technology, with several studies demonstrating the benefits of LVADs in end-stage heart failure. The first generation of commercially available LVADs consisted of pulsatile pumps that were successful in unloading the failing heart and helping to preserve end organ perfusion, but they were limited by large size and poor long-term durability. Second- and third-generation LVADs use continuous flow technology (axial flow and rotary flow) in a smaller size with improved long-term durability. According to the Interagency Registry for Mechanically Assisted Circulatory Support statistical report, 5521 LVADs have been implanted in the United States between June 2006 and March 2012. Since approval of the continuous flow HeartMate II LVAD for destination therapy in January 2010, the number of mechanical support device implants has almost doubled, averaging >100 devices per month.

**Figure 1.** Examples of implantable cardioverter-defibrillators (ICDs) with 2 different types of left ventricular assist devices (LVADs). Posterior-anterior chest x-ray projections of biventricular ICDs in the presence of HVAD (A) and Heartmate II (B) models of LVAD.
Epidemiology

The reported prevalence of ventricular arrhythmia (VA) after LVAD implantation varies on the basis of patient population (eg, causes of cardiomyopathy, indication for LVAD, type of LVAD), definition of the arrhythmia, method of surveillance, and time of follow-up. However, VAs are common adverse events after LVAD implantation, particularly in the first 30 days. VAs requiring cardioversion or defibrillation occurred in 24% of patients who received a HeartMate II during a median 126-day follow-up period in a bridge to transplant trial.6 Similar findings have been seen in single-center observational studies, where VA have been reported to occur in 22% to 59% of LVAD recipients (Table).6,10–18

Incident VAs are also seen in patients who have not had VA before LVAD implant. Ziv et al14 retrospectively studied 91 consecutive patients who underwent implant of a first-generation Heartmate XVE device. Sixty-three percent of the patients in their cohort had ischemic cardiomyopathy and 42% used amiodarone before LVAD. VAs were defined as ventricular tachycardia (VT) or ventricular fibrillation (VF) detected by ICD interrogation, telemetry, or ECG and lasting ≥30 s or requiring defibrillation or antitachycardia pacing. A total of 32 patients (35%) had VA after LVAD implant. Eighteen patients who had no VT before LVAD implant had de novo monomorphic VT after LVAD implant. Ten patients had de novo polymorphic VT or VF after LVAD implant as well.

VAs are most common in the early postoperative period. In the HeartMate II bridge to transplant study, VA were much more common in the first 30 days after LVAD implant (annualized rate of 2.55 per patient-year) than in follow-up >30 days (annualized rate of 0.45 per patient-year).6 This supported observations by Ziv et al14 that 31 of 32 patients who had VA after first-generation LVAD implant had their first episode within 2 weeks of surgery. Andersen et al17 noted 9 of 12 patients (75%) who had sustained VT or VF experienced the arrhythmias within 4 weeks of LVAD placement. Other investigators have also reported similar findings, with VA occurring frequently during the early postoperative period and decreasing over the longer term.18,19 Mechanisms of VA in early and late postoperative periods have not been elucidated, but it is likely that perioperative adrenergic stimulation and the use of adrenergic agonists may play an important role in promoting early arrhythmias, whereas positive cardiac remodeling on LVAD support may be important in decreased VA later during follow-up. It is also important to note that although the majority of arrhythmias occur early, limited data suggest that a quarter to a third of patients may experience their first VA after 30 days.5,18

Both baseline factors and type of LVAD predict risk for VA. In 2 multivariable analyses, a previous history of VA before LVAD placement was associated with incidence of arrhythmias after LVAD implant.18,20 Several studies have also shown that ischemic pathogenesis of cardiomyopathy is a predisposing factor for VA after LVAD placement.13,14,16,21

The type of implanted assist device can also predict risk of VA. In a retrospective study of 124 patients with LVAD and 71 patients with bi-VAD, there was a significant 2-fold increase in risk for developing any type of arrhythmia in LVAD recipients versus bi-VAD recipients after adjusting for multiple variables.19 In addition, several studies have shown an increased incidence of VA in continuous flow pumps compared with pulsatile pumps.10,12,17 In a study reported in abstract, comparing the continuous flow HeartMate II with the pulsatile flow HeartMate XVE,10 there was a 2-fold increase in rate of perioperative VT in HeartMate II compared with HeartMate XVE. There were also significantly fewer HeartMate XVE patients who required antiarrhythmic therapy on discharge. Although confounding is a possible explanation, the unique arrhythmogenicity of suction events has been raised as a potential explanation for more VA events in the setting of continuous flow LVADs (see description in Potential Mechanisms section).10,22

VA Presentation and Prognosis

The presentation of VA in patients with LVAD is variable. Patients supported by LVADs may tolerate VA with minimal symptoms and stable hemodynamics because of the LVAD’s ability to maintain cardiac output independent of heart rate and atrioventricular synchrony.21,23–26 However, some patients with LVAD can experience right heart failure, hemodynamic deterioration, ICD shocks, and even cardiac arrest with VA caused by impaired right ventricular filling leading to inadequate LVAD flows. Uncontrollable VA can be an indication for heart transplantation, bi-VAD, or total artificial heart. LVADs can occasionally be used to manage VA by providing hemodynamic stability during prolonged episodes of VT or VF.21,24–28

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VA indicates ventricular arrhythmia.
In addition to morbidity, there is some concern that VA could lead to mortality in patients with LVADs. In the setting of LVAD for bridge to transplant, Bedi et al\textsuperscript{13} reported a significantly higher mortality rate for patients who experienced VA compared with those without (33% versus 18%; \(P<0.01\)). In addition, patients who had VA within the first week after LVAD placement had 5-fold higher mortality when compared with late presentation of VA (54% versus 10%; \(P<0.01\)). The same population also had lower rates of successful transplantation. Brenyo et al\textsuperscript{29} found a similar increase in mortality in patients with VA after LVAD implant. The increase in mortality was most significant within the first month after LVAD. It is unclear whether VA directly causes mortality in LVAD recipients or serve primarily as markers for patients who are at risk for nonarrhythmic causes of death.

**Potential Mechanisms**

Recipients of LVADs are at risk for arrhythmias at baseline because of their advanced stage of cardiomyopathy. There are several hypothesized mechanisms of arrhythmias unique to LVADs. The apical insertion site of LVAD inflow cannula has been correlated to morphologic origin of monomorphic VT,\textsuperscript{14} although 75% of mapped VTs during ablation correlated to intrinsic myocardial scar rather than the inflow cannula.\textsuperscript{30} A significant increase in monomorphic VT was also seen in a study of LVAD suction events.\textsuperscript{22} Suction events result from mismatch between LVAD outflow and inflow when left ventricular filling does not match the LVAD output. In such a scenario, the left ventricle is excessively unloaded and can partially or fully collapse, which can induce sustained or non-sustained VA that are monomorphic or polymorphic.

In addition, acute mechanical unloading of the left ventricle can lead not only to myocardial structural changes, but also to changes in electrophysiology properties.\textsuperscript{31–33} In particular, repolarization abnormalities have been seen after LVAD implant. In a retrospective study by Harding et al\textsuperscript{31} of 23 patients who underwent LVAD placement, there was a significant increase in QTc within 1 week after LVAD (from 479±10 to 504±11 ms; \(P<0.01\)). The QTc once again decreased after ≥1 week of mechanical support (from 504±11 ms to 445±11 ms; \(P<0.001\)) for the 7 patients with follow-up of ≤1 month and the 16 patients with follow-up >1 month. Increased QTc immediately after LVAD placement has been associated with a 3-fold higher risk for postoperative VA.\textsuperscript{16} Thus, in addition to conventional scar-based reentry and automaticity, triggered activity caused by repolarization abnormality (indicated by QTc prolongation) could represent an additional mechanism for the frequent occurrence of VA in the immediate post-LVAD period. The observed reduction in QTc and QRS intervals with longer duration of LVAD support suggests positive electrophysiological remodeling,\textsuperscript{31} which may explain the decrease in VA incidence over time after LVAD implantation.

**Medical Therapy**

Despite the burden and significance of VA after LVAD implant, prevention and management of arrhythmias with medical therapy in patients with LVADs has only been studied in small, retrospective reports. In a retrospective study of 42 patients with LVAD, multivariable analysis showed a significant association between nonuse of \(\beta\)-blocker after LVAD placement and increased risks for VA.\textsuperscript{15} However in a prospective study of 23 patients with HeartMate II, postoperative treatment with \(\beta\)-blockers did not lower the incidence of arrhythmia, though this study was limited by a small sample size.\textsuperscript{17}

Similar to other clinical settings, maximum tolerated doses of \(\beta\)-adrenergic antagonists are used as first-line treatment for patients with VA after LVAD. For those with recurrent VA or electrical storm who are refractory to (or intolerant of) \(\beta\)-adrenergic antagonists, intravenous amiodarone and lidocaine can be used acutely. Oral amiodarone is often used for VA suppression in the outpatient setting or in-hospital after acute control has been achieved with intravenous antiarrhythmic agents. Mexiletine can be added for patients with successful use of lidocaine for adequate acute control or who have breakthrough VA, despite chronic use of amiodarone. Sotalol can be used as an alternative if amiodarone is not tolerated or there are concerns about toxicities. Finally, close attention to potassium and magnesium levels and avoidance of QT prolonging medications should be considered, particularly early postoperatively.

As for any patient with heart failure with VA, clinicians should consider whether decompensated hemodynamics could be contributing to the arrhythmogenic milieu. In the setting of LVADs, this requires interrogation of the LVAD and consideration of echo or right heart catheterization. Potential interventions include pharmacological treatment of preload and afterload and adjustments to LVAD speed.

**ICD Therapy**

ICD therapy is used for prevention of sudden cardiac death after LVAD implant. The populations of both LVAD and ICD candidates are similarly composed of patients with symptomatic heart failure with reduced left ventricular ejection fraction. As a result, the majority of patients receiving LVAD already have an ICD.\textsuperscript{8} Concurrent ICD and LVAD therapy is feasible and safe,\textsuperscript{12} but the benefit of ICD therapy in an LVAD population has not been tested in a rigorous, randomized fashion. Nonetheless, Cantillon et al\textsuperscript{19} reported in an observational study that patients with LVAD with concomitant ICD had significantly lower all-cause mortality than those without. In addition, a greater number of patients with ICDs survived to receive cardiac transplantation. Data on the impact of first ICD implant after LVAD implant are limited, but shows that there is a high rate of ICD therapies for VT or VF in this population, even with fairly conservative ICD programming.\textsuperscript{20} Thus, some centers routinely implant an ICD after LVAD (Figure 2).

Optimal ICD programming has not been defined. Given the high burden of VA and their potential to be well tolerated hemodynamically, extrapolation of programming strategies demonstrated to reduce mortality among patients with non-LVAD may be warranted.\textsuperscript{24} Use of either prolonged detection time (60 s for rates 160–199 beats per minute; 12 s for rates 200–249 beats per minute; and 2.5 s for rates ≥250 beats per minute) or higher rate cut-offs (single zone ≥200 beats per minute with 2.5 s detection time) should be considered. Use of VT monitoring zone at lower rates may be warranted for investigation of patients with unexplained symptoms. Depending on symptoms and burden of VA and ICD therapies,
some patients with LVAD may require frequent follow-up in electrophysiology clinic or with remote ICD monitoring.

It is important to recognize the potential for LVAD and ICD interaction. There have been several reports of LVAD and ICD incompatibilities caused by electromagnetic interference from HeartMate II LVAD impairing ICD telemetry communication to the programmer. This incompatibility is relatively uncommon, and Fas VR V-193, Epic+VR V-196, Epic+HF V-350) and 1 Sorin ICD (Ovatio DR). ICD lead characteristics can also be affected after LVAD implant. Two studies reported that after LVAD implant, right ventricular ICD leads have a decrease in R-wave amplitude, a decrease in impedance, and an increase in capture threshold even among leads that with previous, chronically stable characteristics. This can result in various ICD problems, including failure to sense VAs, failure to capture, and inappropriate pacing caused by undersensing. We have also observed interference that likely resulted from interaction of a very apically placed chronic right ventricular defibrillator lead with the inflow cannula apparatus (Figure 3). ICD interrogation and reprogramming should be done after LVAD implant. In some cases, lead testing, revision, or replacement may be needed to ensure appropriate ICD function.

Ablation Therapy

Although LVAD implant may help patients tolerate sustained VA, patients may continue to experience symptomatic or hemodynamically significant refractory VA, despite LVAD support. Even slower VTs can lead to hemodynamic decompensation or cardiac arrest in some patients if there is underlying right ventricular dysfunction or pulmonary hypertension that impairs left ventricular filling (and consequently LVAD inflow). Radiofrequency ablation therapy has been described as a therapeutic option in several reports. Dandamudi et al

Figure 2. Perioperative arrhythmia planning for ventricular assist device (VAD) implantation.* Many centers have come to the conclusion that the relative benefits of implantable cardioverter-defibrillator (ICD) use for patients with left VAD exceed the risks for many patients and implant ICDs when not already present for patients at higher risk (pre-VAD ventricular arrhythmia [VA], hemodynamic intolerance of VA post-VAD, etc). Conservative programming with prolonged detection time and high rate cut-offs may lessen the chances of unnecessary shocks (see Discussion section of this article). EP indicates electrophysiology; and Rx, prescription.

Figure 3. Example of interaction between an implantable cardioverter-defibrillator (ICD) and left ventricular assist device (LVAD) because of close proximity of lead and inflow cannula. Close proximity of the ICD lead to the LVAD inflow cannula shown in A was confirmed on lateral chest x-ray (not shown). The interference from this device interaction led to multiple ICD shocks, one of which is shown in B (the immediately preceding antitachycardia pacing is not shown).
described 3 patients with recurrent hemodynamically significant VTs, despite implantation of LVADs who underwent successful VT ablation with complete resolution of VT episodes. Although LVAD implantation was unsuccessful in preventing VT, it provided at least some hemodynamic stability allowing careful mapping of the VT substrate, which was associated with better ablation outcomes. A series by Cantillon et al described 32 diagnostic and ablation procedures (out of 611 LVAD implantations). Overall, 90% of the procedures were performed for VA that were refractory to medical management with amiodarone, mexiletine, or sotalol. Sustained monomorphic VT was inducible in 81% of patients at an average cycle length of 339±59 ms. Three-dimensional electroanatomic mapping with scar voltage mapping was used in 95% of patients. Arrhythmia activation mapping was performed in 60%. The dominant mechanism for VA was intrinsic myocardial scar, with only 14% of VT circuits involving the apical inflow cannulation site. Ablation was acutely successful (VT noninducible) in 86% of patients, with freedom from recurrent VT of 67% during a mean duration of LVAD support of 120 days. Despite a low complication rate (1 femoral artery pseudoaneurysm), ablation therapy in this study and at many centers is conservative and is reserved for patients failing medical therapy who are not candidates for transplantation.

There are a number of unique aspects to VT ablation in patients with LVADs that should be considered. A transseptal approach to the left ventricle, often using a deflectable sheath, is usually necessary because the aortic valve has often been oversewn during surgery or its leaflets can fuse postoperatively. During all ablations in patients with LVADs, we require that an advanced practitioner well-trained in the operation of mechanical assist devices is present to monitor the device, monitor patient blood pressures, and adjust device speed during periods of dynamic preload or afterload. A larger than average lesion set can be undertaken as long as there is not an expectation for reversal of cardiomyopathy over time with mechanical unloading. However, care must still be taken to avoid steam pops and perforations because successful pericardiocentesis can be challenging or impossible in the setting of prior sternotomies. To avoid LVAD thrombus formation, reversal of anticoagulation after ablation is discouraged unless there has been a major bleeding complication.

Suggested Management Approaches

If at all possible, we recommend that patients with LVAD be managed or comanaged by electrophysiologists at the LVAD implanting institution because even after LVAD implantation patients are likely to return for subsequent hospitalizations. Reliable written communication between referring and referral centers is critical. Patients who have isolated ICD shocks after LVAD should be assessed to determine whether the ICD therapy was appropriately treating VA or inappropriately treating artifact or supra-VAs (Figure 4). For any appropriate therapies, it is important that electrophysiologists involve heart failure cardiologists and the ventricular assist device team...
early to determine potential causes and give input on treatment plans. Patients with recurrent VA after LVAD require multidisciplinary inpatient care at an experienced institution (Figure 5).

Conclusions
LVADs have become an important treatment option for the growing number of patients with end-stage heart failure. LVAD management is commonly complicated by VA in early the postoperative period and sometimes in the later postoperative period. Pre-LVAD history of VA and ischemic cardiomyopathy seem to be associated with increased incidence of VA. LVADs can provide hemodynamic support during VA; however, VAs in the setting of LVADs are still associated with significant morbidity and mortality. Limited literature suggests potential benefit from use of β-blockers, amiodarone, and sodium channel blockers; these issues warrant further study.1,7,41 ICD therapy is generally safe and may decrease mortality, leading some centers to use ICDs for all patients with LVAD. Ablation therapy is generally safe and may decrease mortality, leading to continuous-flow device in patients awaiting heart transplantation. N Engl J Med. 2007;357:885–896.


Key Words: arrhythmia (heart rhythm disorders) ■ heart failure ■ ischemic heart failure ■ ventricular assist device ■ ventricular assist device remodeling
Ventricular Arrhythmias After Left Ventricular Assist Device
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