Advances in Mechanical Circulatory Support

Imaging for Ventricular Function and Myocardial Recovery on Nonpulsatile Ventricular Assist Devices

Jerry D. Estep, MD; Su Min Chang, MD; Arvind Bhimaraj, MD, MPH; Guillermo Torre-Amione, MD, PhD; William A. Zoghbi, MD; Sherif F. Nagueh, MD

Advances in the field of device support have led to increased use of continuous-flow left ventricular assist devices (LVADs) to improve outcomes in patients with end-stage heart disease. Newer-generation LVADs have become the pump of choice for bridging to heart transplantation and as destination therapy for patients with contraindications to transplantation. Different imaging modalities have played a major role in LVAD preoperative, early postoperative, and long-term follow-up management. The primary imaging modality to monitor patients with continuous-flow LVADs is echocardiography. The present review highlights the role of echocardiography and the other imaging modalities in the assessment of ventricular size and function, intracardiac hemodynamics, and myocardial recovery of patients with continuous-flow LVADs. The evolving role of echocardiography in facilitating the identification of optimal pump speed settings in patients supported by continuous-flow LVADs will be discussed, along with a summary of the protocol we use for image acquisition and reporting. Furthermore, we will provide a summary of echocardiographic findings associated with continuous-flow LVAD-related complications and device dysfunction.

Types of Continuous-Flow LVADs

Second-generation continuous-flow LVAD rotary pumps offer several advantages over pulsatile first-generation pumps, including smaller size and, importantly, greater long-term mechanical reliability. The different types of continuous-flow LVADs and device characteristics, including pump speeds, are listed in Table 1. The rotating impeller within the pump generates either axial flow (blood flow parallel to the impeller axis) or centrifugal flow (blood flow at a right angle to the impeller axis) from the left ventricular (LV) apex, through the device, to the ascending aorta. The HeartMate II (HM II; Thoratec Corp, Pleasanton, CA) is the only continuous-flow pump approved by the US Food and Drug Administration to act as a bridge to cardiac transplantation and as destination therapy. Operating speeds for this device are between 6000 and 15 000 revolutions per minute (rpm), which clinically translates into very minimal, partial, and full circulatory support capabilities, with a maximum pump flow of 10 L/min. Suitable hemodynamic support and clinical stability are generally offered at pump speeds of approximately 9000 to 10 000 rpm for the HM II and Jarvik (Jarvik Heart, Inc., New York, NY) devices and at 2600 to 2900 rpm for the HeartWare (HeartWare International, Inc., Framingham, MA) HVAD. Knowledge of the type of device and pump speed has implications for cardiac imaging, because they affect LV unloading and ventricular size and function.

Evaluation of Ventricular Size and Function by Echocardiography

LV Size

LVADs provide excellent unloading of the LV, which is associated with a significant reduction in LV dimensions and improved LV systolic performance. The degree of underlying hemodynamic support for continuous-flow pumps, as reflected by the LV end-diastolic diameter, is dependent on preload, afterload, and, importantly, pump speed. Lower levels of continuous-flow pump support are often associated with normal or partial aortic valve (AV) opening and larger LV size measurements. Although M-mode is the conventional standard for LV dimensional analysis, linear measurements from 2-dimensional images are reproducible. Two-dimensional linear measures of LV function may be problematic when there is marked regional difference in function, paradoxical septal motion, or marked septal motion abnormality secondary to interventricular dependency, findings not uncommon in patients supported by LVADs; however, in our experience, 2-dimensional–guided M-mode LV linear dimensions can be measured easily from the parasternal view.

A recent study of 63 stable outpatients with normal-functioning HM II devices noted that efficient LV unloading was associated with a 17% reduction in LV end-diastolic...
diameter 3 months after LVAD implantation (5.6 ± 1.1 versus 6.8 ± 0.9 cm pre-LVAD). Although LV volumes provide a more accurate assessment of LV size, their accurate measurement, unlike LV dimensions, can be challenging from the standard apical view because of the apical inflow cannula and its associated shadowing/attenuation artifact, in addition to echocardiographic dropout at the apex. Because of these limitations, ventricular volumes can be underestimated when assessed by echocardiography. However, investigators have used standard echocardiographic measurements (biplane method of discs) to demonstrate a significant reduction (≈47%) in LV size as early as 1 month after continuous-flow LVAD implantation (127 ± 68 versus 242 ± 108 mL pre-LVAD). This reduction in LV size is similar to that reported for pulsatile pumps. In contrast, other studies report decreased LV unloading in patients receiving continuous-flow LVAD support when LV dimensions/volumes were directly compared with those of patients implanted with pulsatile pumps. It is important to recognize that these recent continuous-flow pump studies all assessed LV size at baseline levels of relatively full support. The reported reduction in LV dimensions does not necessarily imply reverse LV remodeling, which is best assessed by decreasing the amount of LVAD support as much as possible while imaging (Figure 1).

In our experience, there are usually problems with heart function, pump function, and/or fluid balance status of patients who have an increase in LV size after an initial reduction during continuous-flow LVAD support. Deviation from the expected reductions in LV size may reflect several situations, including partial LV unloading at lower levels of support, adverse cardiac remodeling secondary to progressive coronary artery disease, development of significant continuous aortic regurgitation (Fig-

Table 1. Adult Continuous-Flow Surgically Placed LVAD Types

<table>
<thead>
<tr>
<th>Continuous-Flow LVAD Types</th>
<th>Pump Design/Location</th>
<th>Pump Speed Range, rpm</th>
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<tbody>
<tr>
<td>2nd-generation LVADs</td>
<td></td>
<td></td>
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<tr>
<td>HeartMate II*</td>
<td>Axial/preperitoneal</td>
<td>6000–15 000</td>
</tr>
<tr>
<td>MicroMed DeBakey pump†</td>
<td>Axial/preperitoneal</td>
<td>7500–12 500</td>
</tr>
<tr>
<td>Jarvik 2000 FlowMaker†</td>
<td>Axial/intrapericardial</td>
<td>8000–12 000</td>
</tr>
<tr>
<td>3rd-generation LVADs</td>
<td></td>
<td></td>
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<tr>
<td>HeartWare HVAD†</td>
<td>Centrifugal/intrapericardial</td>
<td>1800–4000</td>
</tr>
<tr>
<td>DuraHeart LVAS†</td>
<td>Centrifugal/intrapericardial</td>
<td>1200–2400</td>
</tr>
<tr>
<td>Levacor†</td>
<td>Centrifugal/preperitoneal</td>
<td>1000–3000</td>
</tr>
<tr>
<td>Berlin Heart Incor‡</td>
<td>Axial/preperitoneal</td>
<td>5000–10 000</td>
</tr>
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LVAD indicates left ventricular assist device; LVAS, left ventricular assist system; and rpm, revolutions per minute.

Manufacturers for the devices listed are as follows: HeartMate II (Thoratec Corp, Pleasanton, CA); MicroMed DeBakey pump (MicroMed Technologies, Houston, TX); Jarvik 2000 (Jarvik Heart, Inc, New York, NY); HeartWare (HeartWare International, Inc, Framingham, MA); DuraHeart (Terumo Medical Corporation, Somerset, NJ); Levacor (World Heart, Inc, Salt Lake City, UT); and Incor (Berlin Heart AG, Berlin, Germany).

*Clinically available.
†Investigational.
‡Unavailable in the United States.

Figure 1. Increased left ventricle (LV) size with decreased continuous-flow pump speed. A and B, LV end-diastolic diameter (LVEDd) measured from septum to posterior wall in a patient with HeartMate II demonstrates increased LV size at lower levels of pump support (8000 vs 11 000 rpm). Yellow asterisk indicates inflow cannula. C and D, Corresponding M-mode recordings in the same patient.
LV Function

Investigators have used several methods to calculate LV ejection fraction (LVEF) in patients supported by continuous-flow LVADs. One method is based on fractional shortening measured from the parasternal long-axis and/or short-axis views. In this case, LVEF equals $1.7 \times$ fractional shortening. There are, however, major problems with using fractional shortening in these patients because of interventricular dependence and discordant septal and posterior wall motion. Another LVEF calculation uses the Simpson method from the apical 4-chamber view; however, it may be difficult to measure LVEF by the Simpson method solely based on the 4-chamber view, because the presence of the LVAD apical inflow cannula and its associated apical imaging limitations can make apex imaging and measured volumes highly variable and unreliable. In our experience, LVEF quantification for LVAD patients is most reliably and reproducibly performed by the modified biplane method of discs if visualization of the LV appears reliable from the apex, or by the Quinones method, in which multiple diameters are measured from multiple parasternal and apical views from multiple windows. The Quinones method assumes an akinetic apex given the presence of the apical inflow cannula.

Other methods for calculating LVEF with echocardiography-estimated LV stroke volume from the LV outflow tract divided by LV end-diastolic volume may be unreliable given that partial AV opening or intermittent or complete AV closure is common in patients with continuous-flow LVADs (up to 61% to 78%). This leads to a variable LV outflow tract time velocity integral (TVI) and, consequently, beat-to-beat variation in stroke volume estimations. As an alternative, we and others have monitored LV systolic function using fractional area change at the LV midpapillary muscle level in short-axis views for patients with suboptimal apical but adequate parasternal views.

Novel surrogates of LV systolic function in continuous-flow LVAD patients have been proposed and include the AV opening status and apical inflow cannula velocity variation index. AV opening during continuous-flow LVAD depends on the balance between native LV contractility, preload and afterload pressure, and the degree of LV unloading related to the LVAD pump speed setting. Complete AV closure at relatively low levels of pump support (eg, 8000 rpm for the HM II device) reflects compromised LV systolic function, assuming aortic pressure and LV end-diastolic pressure are in the normal range. The apical inflow cannula velocity variation index is derived from the apical inflow velocity pattern. There is normally a slightly pulsatile velocity inflow pattern because the LVAD pump flow originates from the beating LV, reaching a maximum at peak systole (usually <2 m/s) and a minimum during diastole. Investigators have reported a significant correlation between the systolic-to-diastolic velocity ratio in the apical inflow cannula and LVEF in HM II patients ($r=0.50, P<0.001$). In addition, this novel Doppler index was significantly lower in patients with persistently closed AVs ($3.4\pm1.2$ versus $4.5\pm3.0, P=0.03$).

The clinical importance of monitoring LV systolic function relates to screening for myocardial recovery. Three studies totaling 102 patients supported by continuous-flow LVADs (both axial and centrifugal) reported only mild to moderate improvement in LVEF during relatively full LVAD support, with the mean LVEF remaining <30% between 1- and 6-month follow-up. The clinical observation regarding the decrease in LV volumes with persistent compromise in LV systolic dysfunction mirrors the observation at the myocyte level. When imaging is used to evaluate myocardial recovery in patients supported with continuous-flow LVADs, underlying LV size and function are best assessed when the LVAD support (flow speed) is turned down. Interestingly,
during continuous-flow LVAD support, most patients report significant symptomatic improvement irrespective of LV size and systolic performance.

**RV Size and Function**

In contrast to direct unloading of the LV during continuous-flow LVAD support, the beneficial effect on the right ventricle (RV) appears secondary to a reduction in elevated pulmonary artery pressure.\(^1\) Although the incidence of RV failure in patients with an HM II device is comparable to or less than that in patients with pulsatile devices, right-sided heart dysfunction continues to contribute significantly to postoperative morbidity and mortality.\(^2\) RV dysfunction after LVAD-mediated LV unloading in part relates to acquired interventricular dependency. With reduced LV pressures, bowing of the interventricular septum away from the RV into the decompressed LV can alter RV shape and size and reduce the efficiency of RV contraction by destabilizing the fulcrum on which the RV contracts.\(^3\) In addition, the RV may be further challenged by the increased venous return (preload) provided by the LVAD’s effect on increased systemic blood flow, which is increased at higher pump-speed settings.\(^4\) Several RV echocardiographic parameters have been evaluated for monitoring of patients supported by continuous-flow LVADs.\(^5\) These include RV fractional area change (RVFAC) and tricuspid annular plane systolic excursion (TAPSE), both established measurements of RV systolic function.\(^6\) Lam et al\(^7\) reported 80% feasibility of a comprehensive RV function assessment in 21 patients supported by the HM II device, with moderate to very good intraobserver and interobserver variability. In that study, the intraclass correlation coefficient for repeat RVFAC measurements by different observers was 0.76.\(^7\) Others have reported suboptimal study quality in the majority of early postoperative patients, with a fair interobserver variability for RV function indices (intraclass correlation coefficient range 0.50–0.67).\(^6\)

The overall reported experience reflects variability in the observed RV structural and functional changes after continuous-flow LVAD implantation. Topilsky et al\(^5\) demonstrated a 34% increase in RVFAC 3 months after continuous-flow LVAD support (n=63), whereas others\(^7,11,18\) report no significant consistent changes or worsening RV function based on measured RVFAC and tricuspid annular plane systolic excursion. The importance of monitoring imaging indices of RV function after implantation relate to facilitating the detection of right-sided heart failure (HF) and its association with clinical outcome. Maeder et al\(^11\) showed a correlation between improvement in global RV function after LVAD implantation, improvement in renal function, and reduction in mortality at follow-up. Similarly, Lam et al\(^7\) demonstrated that patients with a >10% reduction in RVFAC...
at 1 month compared with baseline had worse quality of life and lower exercise capacity than patients without a significant decrease in RVFAC.

**Assessment of Hemodynamics by Echocardiography**

**LV Filling Pressures**

Standard echocardiography Doppler-derived indices used to evaluate LV filling pressures in HF patients include the mitral valve inflow early (E) and late (A) peak diastolic velocities, the deceleration time of mitral E velocity, tissue Doppler-derived mitral annular velocities (e’), and the E/e’ ratio.29 Given the decrease in mitral E velocity, E/A and E/e’ ratios, and the prolongation of deceleration time in most patients after LVAD implantation, one can conclude that long-term continuous-flow LVAD support is associated with significant reduction in estimated LV filling pressure.5,7,10,13 In most patients, LV unloading accounts for a significant decrease in left atrial volume,5,7 a reduction in pulmonary artery pressures, and subsequent improvement in several RV function parameters. The above Doppler velocities and ratios (relative changes) can be helpful in the evaluation of symptomatic patients supported by continuous-flow LVADs. Ongoing research will examine the clinical applications and hemodynamic correlates of conventional Doppler parameters in the context of partial LV unloading with continuous-flow LVADs.

**Pulmonary Artery Pressure and Pulmonary Vascular Resistance**

Systolic pulmonary artery pressure and pulmonary vascular resistance (PVR) decrease significantly with continuous-flow LVAD support.5,7,10 These conclusions are based on estimates of systolic pulmonary artery pressure made with use of the peak tricuspid regurgitation jet velocity and PVR as determined with the noninvasively derived ratio between peak tricuspid regurgitation velocity and RV outflow tract (RVOT) TVI.7,30 Recent reports using continuous-flow devices have demonstrated their efficacy in improving medically refractory pulmonary hypertension.31,32 Echocardiography is the first-line imaging modality to monitor pulmonary hypertension, which is especially important for patients with significantly elevated PVR who are being supported by LVADs as a bridge to transplantation (Figure 3). Lam et al7 demonstrated the clinical importance of measuring PVR by echocardiography in patients supported by the HM II. Those who had >50% reduction in PVR 1 month after LVAD placement had better quality of life and higher exercise capacity at 6 months than patients with lower reductions in PVR.7 Although useful for tracking relative trends in pulmonary artery systolic pressure, clinical decisions with regard to transplantation candidacy after LVAD implantation and adjunctive pulmonary hypertension therapy are usually based on direct invasive hemodynamic measurements.33,34 Additional imaging studies are clearly needed to help determine the incremental role of these noninvasive measurements in predicting outcomes in this population.

**RV Cardiac Output and RA Pressure**

With continuous-flow LVADs, the RV cardiac output (CO) represents the systemic CO generated by both the LVAD pump and the native LV when the AV opens at least partially. In patients with persistent AV closure, which may be seen with relatively high continuous-flow pump speeds or very poor native systolic function, the RV CO represents the flow generated by the LVAD pump alone. Investigators have examined the RVOT TVI by pulsed-wave Doppler (Figure 3, bottom) to calculate right-sided stroke volume [(RVOT diameter)² × 0.785 × TVI] and CO.4,7,25 RVOT-derived flow examination can facilitate the evaluation of pump regurgitant flow (LV outflow tract CO – RVOT CO) during pump arrest or during planned Jarvik 2000 off-pump studies4 and the estimation of acquired aortic regurgitation severity after LVAD placement. Continuous aortic regurgitation associated with complete AV closure is being increasingly recognized as a late postoperative clinical finding.14,35 In this scenario, an estimate of aortic regurgitant volume is LVAD stroke volume
(outflow graft cross-sectional area × the outflow graft TVI)\(^5,25,36\)
minus systemic stroke volume (RVOT cross-sectional area × RVOT TVI).\(^37\) Also, given the contribution of RV failure to postoperative morbidity and mortality, echocardiographic detection of elevated right atrial pressure based on the inferior vena cava size response to inspiration and hepatic flow patterns\(^38\) indicating RV failure can be helpful.

**Alternatives to Echocardiography for the Assessment of Ventricular Size, Function, and Hemodynamics**

Alternatives to echocardiography for estimating ventricular function in LVAD patients include multiple-gated acquisition equilibrium radionuclide angiography (ERNA; Figure 4) and electrocardiographically gated cardiac multidetector com-

![Figure 5](image-url)

**Figure 5.** Multidetector computed tomography assessment of left ventricular (LV) ejection fraction (EF). A, LV and right ventricular (RV) EFs derived by application of the Simpson method from base to apex to calculate left and right ventricular end-diastolic (ED) and end-systolic (ES) volumes. B, LV and RV EFs derived by threshold-based 3-dimensional segmentation method to calculate ventricular volumes. Yellow arrows indicate apical inflow cannula. Shaded blue area indicates right ventricle; HR, heart rate.

![Figure 6](image-url)

**Figure 6.** Outflow cannula pulse-wave Doppler profile at normal and very low continuous-flow pump speeds. A, Normal outflow cannula pulsatility velocity pattern with a peak velocity ~100 cm/s after ventricular systole (yellow arrow) in a patient supported by the HeartMate II device (9000 rpm). Note the continuous low-velocity antegrade flow (toward the ascending aorta, above the baseline) obtained from the high right parasternal view. B, Diastolic flow reversal (red arrow marks retrograde flow below the baseline, toward the left ventricle) noted in the outflow cannula to create an off-pump study equivalent with the HeartWare device (1800 rpm), obtained with the high parasternal view. PW indicates pulse wave; HR, heart rate; FPS, frames per second; and SV, sample volume. Panel B was adapted with permission from Wood et al.\(^55\)
Computed tomography (MDCT). Cardiac magnetic resonance imaging, a robust technique to assess ventricular volumes and function, is not an imaging option for LVAD patients because of the metallic LVAD system components. We and others have used ERNA, a well-established technique for LVEF assessment, to monitor LVEF in patients supported by older-generation LVADs. The advantages of ERNA are that the quantitative measurement of ventricular function does not depend on mathematical assumptions of ventricular geometry and that measurements are obtainable in most patients. However, because ERNA is based on planar projection imaging, the RV ejection fraction (EF) measurement could be affected by the overlap of RV and right atrium. The first-pass radionuclide angiography technique is better suited for RV EF assessment but is much more clinically challenging and not routinely performed. A clinical limitation in LVAD patients is the potential long-term risk of radiation exposure from serial examinations used to monitor ventricular size and function; however, unlike MDCT, there is no risk of nephrotoxicity from radionuclide isotopes used for ERNA.

Because of its 3-dimensional approach, isotropic spatial resolution, and exceptional image quality, MDCT may offer a more accurate quantitative measurement of ventricular volume changes throughout the cardiac cycle, as well as information on global EF and regional LV function. This is especially true in the assessment of asymmetrical RVs. MDCT assessment of ventricular EF and volume can be performed with 2-dimensional planimetry of short-axis computed tomography image reformations (Simpson method) or with a more automated threshold-based 3-dimensional augmentation approach (Figure 5). One study in 36 patients explored the role of cardiac MDCT in the assessment of ventricular function in patients with continuous-flow LVADs. Systemic CO can also be determined with dynamic computed tomography, which has good agreement with standard invasive thermodilution measurements. Further validation of the role of cardiac MDCT (as it relates to ventricular size, function, and hemodynamic assessment) in larger studies is needed. A limitation of cardiac MDCT relates to the risk of nephrotoxicity from iodinated contrast agents and radiation.
exposure, an important consideration in this patient population given the potential need for serial examinations.

There are currently no reported studies comparing the measurement of cardiac volume and EF using all 3 imaging methods (echocardiography, ERNA, and MDCT) in the same patients; however, wide variations have been noted in EF and volume measurements with echocardiography, ERNA, and cardiac magnetic resonance imaging in patients with stable HF.\textsuperscript{44} The variances appear more pronounced with echocardiography techniques. Therefore, it is highly likely that LVEF and volumes obtained by different imaging techniques in the same LVAD patient are not interchangeable, with important implications from clinical and research perspectives. However, the day-to-day utility of the different techniques depends on local expertise, ease of access, presence or absence of contraindication to contrast, and whether there is a need for precise quantitative measurement, as in the setting of myocardial recovery. In patients with a continuous-flow LVAD as a bridge to heart transplantation, accurate tracking of changes in ventricular EF is usually less important.

Myocardial Recovery

The concept of LVAD support as a bridge to myocardial recovery has been cited as a major goal after device implantation.\textsuperscript{45} Despite initial enthusiasm, significant myocardial recovery after continuous-flow LVAD therapy occurs in only a small percentage of patients with advanced HF (1% to 4%)\textsuperscript{46,47}; however, there is higher incidence of myocardial recovery when the clinical profile includes younger age, shorter duration of HF, minimal pre-LVAD baseline LV remodeling assessed by LV size, and nonischemic origin (ie, myocarditis).\textsuperscript{15,46,48–51} In addition to consideration of elective LVAD removal on the basis of functional ventricular recovery, device removal is clinically considered when overt pump malfunction occurs or recurring device-related complications exist (ie, infection).

In the setting of elective or clinically indicated LVAD explantation, the goal of imaging is to predict long-term clinical stability after device removal. The echocardiographic parameters evaluated for the prediction of cardiac recovery include measures of ventricular size (LV end-diastolic diameter, LV end-systolic diameter, and RV diameters), indices of ventricular systolic function (LVEF and RV EF), and echocardiography-derived hemodynamic parameters.\textsuperscript{46,48,52–55} For patients supported by pulsatile LVADs, pharmacological and exercise stress echocardiography during off-pump and partial LVAD support have been examined in the detection of myocardial recovery.\textsuperscript{4,25} Because continuous-flow pumps have no valves, a total pump stop (off-pump testing) may result in a backflow of blood into the LV, which could lead to a significant additional volume load that would confound the assessment of LV size and function. Brief (<5 minutes) off-pump testing, however, has been performed for the Jarvik 2000, with noted minimal regurgitation through the device into the LV, which suggests this form of testing was tolerated.\textsuperscript{4,25} Although such an examination may be helpful to

Figure 8. Echocardiography pump-speed change study to decrease severity of mitral regurgitation. A, Four-chamber apical view demonstrates severe mitral regurgitation (~40% of left atrium cross-sectional area, red arrow) at HeartMate II baseline speed of 9000 rpm. This is, in part, secondary to apical inflow posterior malposition (red asterisk) noted from the parasternal long-axis view with associated posterior leaflet malcoaptation. See online-only Data Supplement Movie III. B, Severity of mitral regurgitation minimized by echocardiography color Doppler guidance to increase pump speed to 11 000 rpm. See online-only Data Supplement Movie IV.
assess underlying ventricular size and function, testing can be performed safely and easily by decreasing the Jarvik pump speed.58

Blood flow through continuous-flow devices depends primarily on the difference between LV and aortic pressure across the pump when the impeller speed is constant. At the onset of systole, LV pressure rises. As pump flow increases, the pressure difference between the LV and the pump decreases, which results in a peak velocity measured in either the inflow or outflow cannula. During diastole, LV pressure decreases, and blood flow through the inflow and outflow cannula decreases but remains antegrade through the pump (Figure 6A). Therefore, to accomplish safe LVAD weaning under Doppler echocardiography guidance, investigators have reduced the pump speed of continuous-flow LVADs to a level at which no or minimally effective antegrade flow through the outflow graft could be detected (Figure 6B).4,46,54,55,59 Achievement of a mean pump flow of ≈0 L/min as a clinical substitute to clamping the LVAD pump circuit minimizes LVAD support to best estimate native heart function.

The largest published series to examine echocardiographic imaging parameters and cardiac stability included 45 patients with explanted LVADs, 12 of whom (27%) had continuous-flow devices (INCOR or HM II). Parameters with the highest predictive values for >5-year cardiac stability included pre-explantation off-pump LVEF ≥50% with either LV end-diastolic diameter ≤55 mm or a history of heart failure (≥5 years).55,59 Reportedly, with each unit of LVEF reduction, the risk of HF recurrence became 1.5 times higher. In this cohort of patients, a >10% increase in LV size or >10% reduction in relative wall thickness (a surrogate for increased wall stress) during the weaning trial also appeared to be risk factors for clinical instability after LVAD removal. Although there is no uniformly accepted LVAD echocardiography weaning protocol to predict long-term myocardial recovery, the decision for device removal is usually based on clinical criteria that include patient stability and measured imaging parameters of ventricular structure and function. A general imaging protocol based on our experience and criteria related to LVAD-related MR (posterior malpositioned inflow cannula with incomplete MV coaptation secondary to posterior leaflet tethering and moderate to severe MR)

Intracardiac thrombus (including right and left atrial, LV apical, and aortic root thrombus)
Apical inflow abnormality caused by inflow cannula obstruction, malposition, or hyperdynamic apical LV function (color Doppler high-velocity aliasing flow at the cannula orifice with a peak Doppler velocity >2 m/s)
Outflow cannula kinking or thrombosis (partial-elevated peak outflow cannula velocity ≥2 m/s; complete-loss of Doppler signal and no RV outflow tract stroke volume increase and/or no decrease in LV linear end-diastolic diameter dimension with pump-speed increases)
Hypertensive emergency (minimal AV opening, dilated LV, worsening MR, and peak outflow cannula velocity >2 m/s)
Impeller cessation (dilated LV, acute reversal of apical inflow flow direction with spectral or color Doppler, worsening MR, and decreased RV outflow tract stroke volume; loss of inflow cannula reverberation artifact with intrapericardial devices; and/or no decrease in LV linear end-diastolic diameter dimension or reduction in AV opening with pump-speed increases)
LVAD indicates left ventricular assist device; LV, left ventricle/left ventricular; MR, mitral regurgitation; RV, right ventricle/right ventricular; MV, mitral valve; and AV, aortic valve.

Table 2. Continuous-Flow LVAD Postimplantation Complications and Device Dysfunction Detected by Echocardiography

<table>
<thead>
<tr>
<th>Event</th>
<th>Definition</th>
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<tr>
<td>LV failure secondary to partial LV unloading</td>
<td>Increased mitral inflow peak E wave diastolic velocity, increased E/A and E/e’ ratio, decreased deceleration time of mitral E velocity, increased left atrial volume, worsening functional MR, and elevated pulmonary artery systolic pressure</td>
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<td>RV failure</td>
<td>Increased RV size, decreased RV systolic function, increased right atrial pressure, increased tricuspid regurgitation, interstitial septum shifted to the left, reduced RV outflow tract stroke volume, reduced spectral Doppler of LVAD inflow and outflow velocities, ie, &lt;0.5 m/s with severe failure</td>
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<tr>
<td>Inadequate LV filling or excessive LV unloading (small LV dimensions and/or marked deviation of the interventricular septum toward the LV)</td>
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<tr>
<td>LVAD-induced ventricular ectopy or tachycardia</td>
<td>Underfilled LV and mechanical impact with endocardium</td>
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<td>LVAD-related continuous aortic insufficiency (aortic regurgitation throughout cardiac diastole and systole) at least moderate to severe severity characterized by a regurgitant jet to LV outflow tract height ratio &gt;47%, relative decreased RV outflow tract stroke volume, and increased LV size</td>
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<tr>
<td>LVAD-related MR (posterior malpositioned inflow cannula with incomplete MV coaptation secondary to posterior leaflet tethering and moderate to severe MR)</td>
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<tr>
<td>Intracardiac thrombus (including right and left atrial, LV apical, and aortic root thrombus)</td>
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<tr>
<td>Apical inflow abnormality caused by inflow cannula obstruction, malposition, or hyperdynamic apical LV function (color Doppler high-velocity aliasing flow at the cannula orifice with a peak Doppler velocity &gt;2 m/s)</td>
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<tr>
<td>Outflow cannula kinking or thrombosis (partial-elevated peak outflow cannula velocity ≥2 m/s; complete-loss of Doppler signal and no RV outflow tract stroke volume increase and/or decrease in LV linear end-diastolic diameter dimension with pump-speed increases)</td>
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<td>Hypertensive emergency (minimal AV opening, dilated LV, worsening MR, and peak outflow cannula velocity &gt;2 m/s)</td>
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<td>Impeller cessation (dilated LV, acute reversal of apical inflow flow direction with spectral or color Doppler, worsening MR, and decreased RV outflow tract stroke volume; loss of inflow cannula reverberation artifact with intrapericardial devices; and/or no decrease in LV linear end-diastolic diameter dimension or reduction in AV opening with pump-speed increases)</td>
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Continuous-flow LVAD removal with echocardiography indices based on AV opening, tissue Doppler imaging, or strain and stain rate. Dandel et al demonstrated that radial or longitudinal systolic peak velocity off-pump values >8 cm/s (obtained from the basal posterior wall) showed a positive predictive value of 86.7% for postweaning long-term cardiac stability.

Imaging-Guided Cardiac Function Optimization

Many centers, including ours, use echocardiography to optimize the pump-speed settings for continuous-flow devices.13,26,46 Echocardiography (transesophageal intraoperatively, transthoracic thereafter) can be used early postoperatively to minimize interventricular septal shift. This avoids the undue LV unloading seen at higher pump speeds, compromised RV systolic function, and incomplete tricuspid coaptation, which can contribute to clinically significant RV failure.62
In our experience and that of others,4,5,25 higher LVAD pump speeds are associated with decreased mid-LV linear dimensions, mitral regurgitation, surrogates for LV filling pressure (lower E/A and E/e' ratios; longer E-wave deceleration time), and AV opening. Echocardiography can be used to detect the pump-speed setting associated with optimal LV unloading and lower severity mitral regurgitation (Figure 8) while avoiding complications related to high pump flow (small LV size with inflow cannula-associated ventricular dysrhythmias) in patients with persistent HF symptoms. Echocardiography can also be used to detect the pump speed associated with at least periodic AV opening to potentially minimize aortic root stasis/clot, long-term AV commissural fusion, and acquired long-term aortic insufficiency. Less frequent AV opening may be a risk factor for continuous aortic insufficiency during long-term device therapy.14,35 Acquired high-grade aortic insufficiency after LVAD placement is a potential significant complication in the context of destination therapy, because it has been associated with larger LV volumes, clinical HF, and poorer prognosis.14,26,63 However, the long-term impact of pump-speed changes based on echocardiographic parameters has not been studied prospectively in a large number of patients.

Assessment of Clinical Deterioration or Abnormal LVAD Parameters Associated With Continuous-Flow LVAD Dysfunction

Our approach, and that of others,22–24,26 for assessing a patient with either recurrent HF symptoms, dysrhythmias, or abnormal LVAD system data (pump speed, power, pulsatility index, and pump flow) is based on integrated clinical and imaging results associated with continuous-flow LVAD post-implantation complications and device dysfunction (Table 2). LVAD-related clinical challenges in the presence of a normally functioning LVAD system include HF, excessive LV unloading, intracardiac and aortic root thrombus, and LVAD-related valvular insufficiency. These clinical challenges can be influenced significantly by the underlying baseline pump-speed setting. Direct continuous-flow LVAD complications include device pump malfunction (impeller pump arrest or pump thrombosis), inflow cannula obstruction (thrombosis or intermittent obstruction caused by malposition), and outflow cannula obstruction (thrombosis or kinking). In a normally functioning continuous-flow LVAD, color Doppler studies of inflow and outflow show laminar characteristics and low velocity (Jarvik 2000 peak outflow velocities <0.75 m/s25; HM II peak inflow velocities <0.76±0.3 m/s<sup>2</sup>). Reasons for flow obstruction in the inflow cannula (detected by high peak inflow velocities >2 m/s) include intermittent obstruction of the cannula by the ventricular wall (Figure 9A) or thrombus.13

Echocardiography may be of limited value in detecting LVAD-related complications because of the inability to view the entire device, especially the outflow cannula. Cardiac MDCT, on the other hand, allows for direct and complete visualization of the LVAD cannulas in addition to the aortic root. Cardiac MDCT has become a robust technique for assessment of continuous-flow LVAD complications such as pericardial effusion, cannula kinking and/or cannula malposition, and thrombus (Figures 9B and 9C).13,64,65
As reported previously by us and others, examination of patients with continuous-flow LVADs consists of a standard comprehensive echocardiography examination, similar to any HF patient, with particular attention to ventricular dimensions, systolic function, and intracardiac hemodynamics in addition to AV function and cannula interrogation. We obtain a baseline transthoracic echocardiogram 2 weeks after implantation, at 1 month, and then routinely every 3 to 6 months and as clinically indicated. Others obtain echocardiograms more frequently, weekly for the first few months then monthly thereafter. In addition to standard documentation of demographics, we annotate device type and device pump-speed setting in revolutions per minute. We record 3 to 5 cardiac cycles using both 2-dimensional and M-mode techniques from the parasternal long- and short-axis views to facilitate monitoring of changes in LV and RV size and function in addition to qualitatively assessing ejection through the AV (normal, intermittent, or no AV opening; Figure 10). In patients with a difficult echocardiography window or suspected LVAD malfunction/complication not readily diagnosed by echocardiography, ERNA (to evaluate ventricular function) or MDCT (to evaluate ventricular function or device-related complication) should be considered.

The present review is applicable to imaging of all types of continuous-flow LVADs. Special imaging consideration is given to LVADs with an intrapericardial pump location (ie, Jarvik 2000 and HeartWare), which can be associated with inflow cannula color Doppler artifact (presumably caused by pump-related ultrasound frequencies). Although this artifact may limit the spectral Doppler information obtained in specific views, this can be worked around by using Doppler when views are sufficiently modified to exclude actual images of the inflow cannula.

Conclusions
Cardiac imaging plays a critical role in determining ventricular size, function, and intracardiac hemodynamics in patients supported by continuous-flow LVADs. Echocardiography is the first-line imaging modality to monitor and screen patients for potential long-term myocardial recovery during continuous-flow device support. The concept of using echocardiography during variable pump settings is important not only to bracket the extent of LVAD support as it relates to the assessment of ventricular size and contractility but also to guide pump-speed selection. Findings suggestive of myocardial recovery include an LVEF >50% and near-normal LV end-diastolic diameter (<5.5 cm) both at low levels of continuous-flow support and during repeated LVAD weaning trials. Alternative methodology to assess ventricular size and function include ERNA and MDCT. We have described the application of imaging for ventricular function and myocardial recovery for surgically placed and permanent continuous-flow LVADs. Many of the same device-weaning concepts apply to percutaneous and surgically placed
continuous-flow temporary devices, albeit over a weaning trial duration of days instead of weeks. As continuous-flow devices offer long-term support and become more commonly used, standardized image acquisition and interpretation will aid in the care of these patients.

Disclosures

None.

References


**Key Words:** cardiac imaging techniques ▪ computed tomography ▪ heart failure ▪ heart-assist devices ▪ echocardiography
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Jerry D. Estep, Su Min Chang, Arvind Bhimaraj, Guillermo Torre-Amione, William A. Zoghbi and Sherif F. Nagueh

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