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iREVIEWS

STATE-OF-THE-ART PAPER

The Role of Echocardiography and Other Imaging Modalities in Patients With Left Ventricular Assist Devices

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Recent advances in the field of left ventricular device support have led to an increased use of left ventricular assist devices (LVADs) in patients with end stage heart disease. The primary imaging modality to monitor patients with LVADs has been echocardiography. The purpose of this review is to highlight the clinical role of echo and other noninvasive imaging modalities in the assessment of cardiac structure and function in patients with pulsatile and continuous flow LVADs. In addition, we discuss the role of imaging with emphasis on echo to detect LVAD dysfunction and device related complications. (J Am Coll Cardiol Img 2010;3:1049–64) © 2010 by the American College of Cardiology Foundation

Although heart transplantation (HT) is an ideal option for patients with end stage heart disease, long waiting times have lead to an increase in the use of left ventricular assist devices (LVADs). LVADs can improve quality of life and end organ function in patients with refractory heart failure (1). Although echocardiography (echo) has become the primary imaging modality to facilitate pre-LVAD management and for post-implantation monitoring of patients with all types of LVADs, there are only limited published descriptions for these applications. Echo is an ideal modality to monitor patients after LVAD implantation because it is noninvasive, widely available, and can be performed at the bedside. Accordingly, the purpose of this review is to highlight the evolving clinical role of echo in the assessment of ventricular structure and function, hemodynamics, valvular function, and myocardial recovery in patients with pulsatile and continuous-flow surgically implanted LVADs. In addition, we discuss the role of echo to detect LVAD dysfunction and related complications as well as other noninvasive imaging modalities when the echo examination is limited. We will also provide recommendations to guide image acquisition and reporting to facilitate continued noninvasive monitoring of patients supported by LVADs.

LVAD Types and Function

The different types of LVADs are listed in Table 1. The HeartMate XVE (Thoratec Corp., Pleasanton, California), a pulsatile pump, can be operated in either a fixed-rate

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(partial support) or automatic mode (full support) and can produce a maximum stroke volume of 83 ml at varying rates (from 50 to 120 beats/min), resulting in flow rates from 4 to 10 l/min. Pulsatile LVADs do not routinely require Coumadin use in contrast to the continuous-flow LVADs, which may account for their continued, albeit less common use. Second- and third-generation continuous (axial and centrifugal) flow pumps offer several advantages including smaller size, less noise, and greater long-term mechanical reliability. The HeartMate II pump (Thoratec Corp.) is the only continuous-flow pump currently approved as a bridge to HT and as destination therapy. This device has a pump implant volume of 63 ml and can be operated at a pump speed between 8,000 to 12,000 revolutions/min (RPM), generating flow rates up to 10 l/min (2).

ABBREVIATIONS AND ACRONYMS

AR = aortic regurgitation
AV = aortic valve
CO = cardiac output
CT = computed tomography
echo = echocardiography
HT = heart transplantation
LV = left ventricle
LVAD = left ventricular assist device
LVEDd = left ventricular end-diastolic diameter
LVEF = left ventricular ejection fraction
MR = mitral regurgitation
MV = mitral valve
PVR = pulmonary vascular resistance
RPM = revolutions/min
RV = right ventricle
RVFAC = right ventricular fractional area change
TR = tricuspid regurgitation

Left Ventricular (LV) Structure and Function With LVAD Support

Assessment of linear dimensions. LVADs provide excellent unloading of the left ventricle (LV) and significant reduction in LV dimensions and improvement in LV function. For pulsatile LVADs, device filling and ejection is not timed with the native cardiac cycle and this asynchrony explains why the greatest left ventricular end-diastolic diameter (LVEDd) may not necessarily coincide with end diastole as defined by the electrocardiogram (Fig. 1). For continuous-flow pumps, in contrast, there is a constant degree of hemodynamic support as reflected by the consistent LV internal dimensional changes during the cardiac cycle (Fig. 2A). The LVEDd, which is dependent on preload and afterload, will be influenced by the pump speed. For continuous-flow LVADs, measurements of LV end-systolic and -diastolic diameters are less problematic (Fig. 2B). For pulsatile devices, we recommend measuring the largest LVEDd at the end of mechanical diastole, just after mitral valve (MV) closure and the smallest LV end-systolic diameter. In comparison to measuring LV linear dimensions from the parasternal views, it may be difficult to accurately measure LV volumes using standard apical views due to the apical inflow cannula and associated shadowing or attenuation artifact.

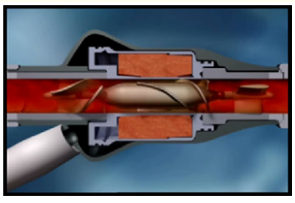
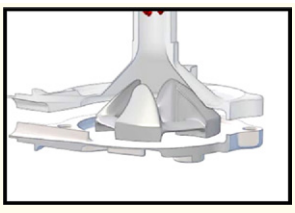
Assessment of function. The clinical importance of following LV systolic function relates to screening for myocardial recovery. Most studies report calculating left ventricular ejection fraction (LVEF) using either the method of disks from the apical view or the fractional shortening method from the parasternal long- and/or short-axis views (3–6). Either approach may have limitations secondary to marked paradoxical septal motion, asynchronous support (pulsatile LVAD), or difficulties of imaging from the apical window. An alternative method is that of the multiple diameter method in 2 views, with the assumption that the apex is akinetic (7). Dalby et al. (8) demonstrated in patients with pulsatile LVADs that the most representative fractional shortening assessment of intrinsic LV performance occurred when the posterior wall motion was greatest and coordinated with septal movement. This type of analysis requires imaging several cardiac cycles. In technically difficult cases, in order to evaluate ventricular function, contrast echocardiography may be used to enhance endocardial visualization or, alternatively, multiple-gated acquisition radionuclide imaging (9).

RV Structure and Function With LVAD Support

The beneficial effect of LVADs on the right ventricle (RV) appears secondary to a decrease in pulmonary artery pressure. Right heart dysfunction is, however, a significant concern after LVAD implantation and contributes to post-operative morbidity and mortality (2). Lam et al. (10) reported that a comprehensive right heart exam can be obtained in 80% of LVAD-echo studies with good intraobserver and interobserver variability in the assessment of RV functional parameters. When severe RV failure occurs, the RV is usually enlarged and significant tricuspid regurgitation (TR) may develop as a consequence of RV and tricuspid annular dilation and severe leftward shifting of the interventricular septum. Associated echo features of RV failure include parameters of elevated right atrial pressure (as judged by interatrial septal motion, tricuspid diastolic inflow, inferior vena cava size, and hepatic flow pattern) and a small LV chamber or collapse of the LV around the inflow cannula.

Predicting RV function after LVAD implantation remains a challenge. The LVAD Working Group (5) observed that LVEF decreases over time in the majority of patients with pulsatile LVADs in contrast to consistent improvement in RV systolic function measured by right ventricular fractional area change (RVFAC). However, 2 groups found

Table 1. Adult LVAD Types

Surgical LVAD Types	Pump Design	Device Illustration
First-generation LVADs HeartMate XVE* Novacor LVAS* Thoratec LVAD*	Pulsatile flow pump	
Second-generation LVADs HeartMate II* MicroMed DeBakey pump† Jarvik FlowMaker†	Continuous flow (Axial flow pump)	
Third-generation LVADs VentrAssist LVAS† HeartWare LVAD† DuraHeart LVAS† Levacor VAD†	Continuous flow (Centrifugal flow pump)	

*Clinically available. †Investigational in the U.S. Thoratec Vented Electric (VE) Heart Mate XVE (Thoratec Corp., Pleasanton, California); Novacor LVAS (World Heart Corp., Oakland, California); Thoratec LVAD (Thoratec Corp.); HeartMate II (Thoratec Corp.); MicroMed DeBakey pump (MicroMed Technologies, Houston, Texas); Jarvik FlowMaker (Jarvik Heart Inc., New York, New York); VentrAssist LVAS (Ventracor, Sydney, Australia); HeartWare (HeartWare Inc., Miami Lakes, Florida); DuraHeart (Terumo Heart Inc., Ann Arbor, Michigan); Levacor (World Heart). Device illustrations: pulsatile (pusher plate pump in housing container); axial flow (blood flows parallel with the impellar axis); centrifugal flow (blood ejected at a right angle to the impellar blades). Blood flow direction is from LV apex to device to the ascending aorta. Device illustrations reprinted, with permission, from Thoratec Corporation.
LV = left ventricular; LVAD = left ventricular assist device; LVAS = left ventricular assist system.

that in a small number of continuous-flow LVAD patients (n = 41), there was significant variability in RV function as measured by RVFAC or tricuspid annular plane systolic excursion (10,11). Importantly, Maeder et al. (11) demonstrated that improved global RV function after LVAD was associated with improved renal function and reduced mortality. Similarly, Lam et al. (10) demonstrated that patients with a greater than 10% reduction in RVFAC at 1 month compared to baseline had worse quality of life and lower exercise capacity compared with patients without a significant change in RVFAC. These findings are consistent with those reported by Simon et al. (12) where post-operative RV function predicted exercise performance as assessed by maximum oxygen consumption.

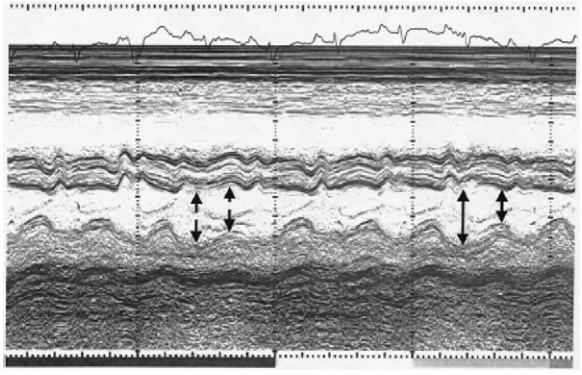


Figure 1. Asynchronous Pulsatile LVAD Support

M-mode recording illustrates significant difference in left ventricular end-diastolic diameter and fractional shortening because of asynchronous pulsatile left ventricular assist device support: smaller values when posterior wall motion is least and septal wall motion is incoordinate **(interrupted arrows)** in contrast to when the posterior wall motion is the greatest along with coordinated septal wall motion **(continuous arrow)**. Adapted, with permission, from Dalby et al. (8). LVAD = left ventricular assist device.

Hemodynamics

In patients with LVADs, total systemic or RV cardiac output (CO) is the sum of intrinsic LV

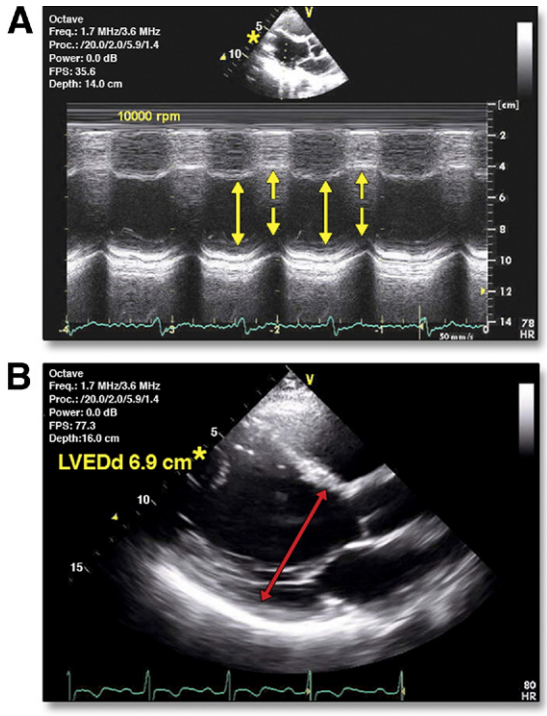


Figure 2. LV Dimension Assessment With Continuous-Flow Pumps

(A) M-mode recording illustrates synchronous LV-LVAD relationship. Consistent LVEDd **(continuous yellow arrow)** and end-systolic dimensions **(interrupted yellow arrow)** are seen albeit with paradoxical septal motion. **(B)** LVEDd measured in centimeters from the septum to posterior wall. **Yellow** * highlights the positioning of the inflow cannula. LVEDd = left ventricular end-diastolic diameter; RPM = revolutions per minute; other abbreviation as in Figure 1.

output through the aortic valve (AV) and that of the LVAD. Both pulsatile and continuous-flow LVADs are associated with a decrease in normal AV opening; the contribution of intrinsic LV systolic function is reflected by the duration and frequency of AV opening (13). Intermittent or variable AV opening is associated with variable left-sided stroke volumes. Using standard Doppler methods, investigators have examined RV cardiac output using pulsed-wave Doppler in the RV outflow tract (Fig. 3) (10,13,14). In patients with persistent AV closure seen with higher LVAD pump speeds and/or very poor native LV systolic function, the RV cardiac output represents the complete flow generated by the pump.

An indirect estimation of pump flow when there is at least partial AV opening is RV cardiac output minus LV outflow tract CO (13,14). With the exception of the MicroMed DeBakey pump (MicroMed Technology, Inc., Houston, Texas), all pump console–reported flows are estimates based on pump power consumption. Therefore, it is our practice to measure and report estimated right-sided CO along with the degree of AV opening by M-mode (normal, partial, intermittent, or complete AV closure) for a qualitative estimate of native aortic outflow. Increasing the pump speed in continuous-flow pumps has been associated with an increase in RV cardiac output, predominately by increasing preload (13). Another potential noninvasive alternative to estimate systemic CO is dynamic computed tomography (CT). Raman et al. (15) demonstrated the feasibility of using signal intensity versus time recordings with contrast-enhanced CT to estimate CO with good agreement when compared with invasive thermodilution measurements (correlation coefficient of 0.74). However, additional and larger validation studies are needed.

Investigators have shown that patients with pulsatile-type LVADs in comparison to those with the DeBakey pump had greater reductions in the mitral E/A ratio and greater prolongation of deceleration time (16). One must consider, however, that higher pump speed settings with continuous-flow pumps may also be associated with greater reductions in LV filling pressure with similar affects on MV inflow parameters (Fig. 4). The accuracy of echo to detect persistently elevated LV filling pressure in patients with continuous flow LVADs is currently under investigation.

Pulmonary Hypertension

Serial Doppler echo assessment of pulmonary artery pressure is important after LVAD implantation. Pulmonary hypertension with a presumed "fixed" component (elevated transpulmonary gradient >15 mm Hg or elevated pulmonary vascular resistance >4 Wood units) is highly associated with RV failure and reduced survival after HT (17). LVAD support offers a suitable alternative in this patient population and may result in pulmonary pressure normalization, permitting transplant candidacy at a later date (18).

Doppler markers of pulmonary artery pressures have been shown to significantly decrease with LVAD support. These include the peak velocity of the TR jet (proportional to pulmonary artery systolic pressure as shown in Figure 5), the pulmonary vein acceleration time (inversely proportional to mean pulmonary artery pressure), and estimated pulmonary vascular resistance (PVR) using the Abbas formula [(maximum tricuspid velocity/RV outflow tract time-velocity integral) × 10 + 0.16]

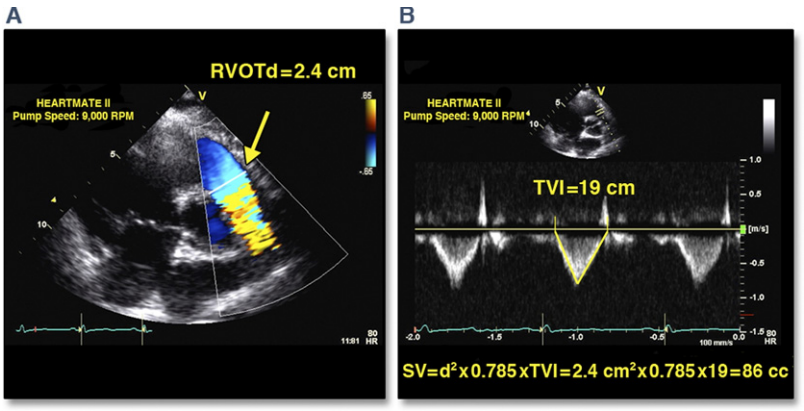


Figure 3. Systemic Cardiac Output Assessment

(A) Right ventricular outflow tract diameter assessment. **(B)** Time velocity integral by pulsed Doppler in the right ventricular outflow tract. The calculated stroke volume (86 cc) at a heart rate of 80 beats/min equates to a cardiac output of 6.8 l/min. RVOTd = right ventricular outflow tract diameter; SV = stroke volume; TVI = time velocity integral.

(10,16,19). In this regard, echo is the first line exam to screen for pulmonary hypertension in patients supported by LVADs, especially for patients where anticoagulation is required and invasive testing is less attractive. In addition, Lam et al. (10) demonstrated the clinical importance of measuring PVR in patients supported by the HeartMate II (Thoratec Corp.). Those who had >50% reductions in PVR 1 month after LVAD placement had better quality of life and higher exercise capacity at 6 months compared with patients with lower reductions in PVR (10).

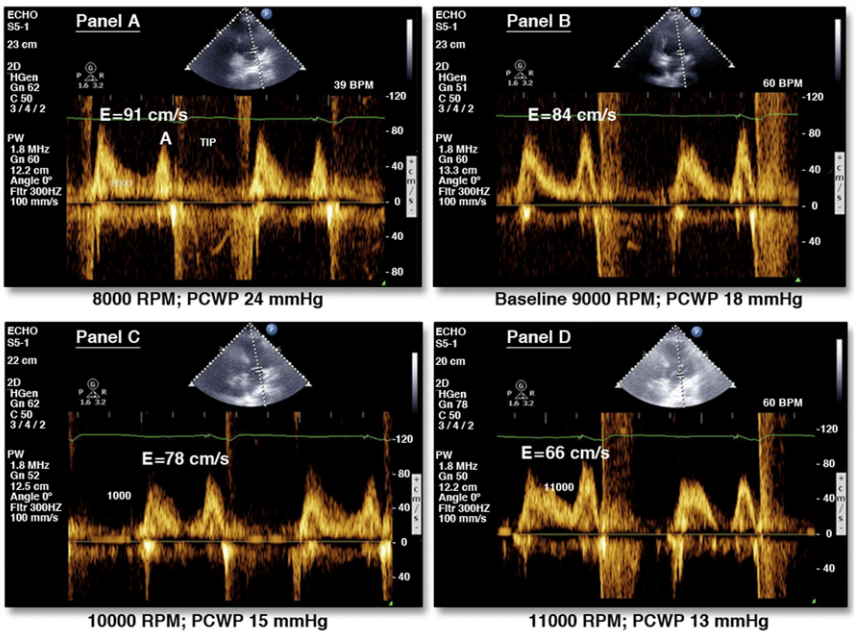


Figure 4. Mitral Valve Inflow Doppler Pattern at Various Continuous-Flow LVAD Pump Speed Settings

The E-wave velocity, E/A ratio, and pulmonary capillary wedge pressure (measured simultaneously) decrease with increasing left ventricular assist device pump speed from 8,000 to 11,000 revolutions/min **(A to D)** in a patient with the HeartMate II (Thoratec Corp.) left ventricular assist device. A = late peak mitral valve inflow velocity; E = early peak mitral valve inflow velocity; PCWP = pulmonary capillary wedge pressure; other abbreviations as in Figures 1 and 2.

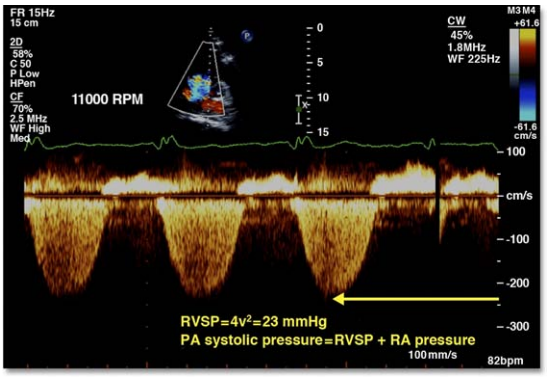


Figure 5. Pulmonary Pressure Assessment During LVAD Support

Estimated systolic pulmonary artery pressure obtained from the peak tricuspid regurgitation jet velocity using continuous-wave Doppler and the modified Bernoulli equation. PA = pulmonary artery; RA = right atrium; RVSP = right ventricular systolic pressure; v = peak tricuspid regurgitation velocity; other abbreviations as in Figures 1 and 4.

Valvular Assessment With LVAD Support

Mitral regurgitation (MR) is often significantly reduced after LVAD placement secondary to reduced LV size, filling pressures, and improved coaptation of the MV leaflets (20). Given that pulsatile LVADs operate in a full-to-empty mode, the reduction in degree of MR appears greater with pulsatile compared with continuous-flow LVADs (16,21). Persistence of significant MR after continuous LVAD placement may indicate inadequate LV decompression. In our experience, changing the pump speed setting with real-time echo imaging can be used to evaluate the effect of various pump speeds on LV dimensions, MV inflow parameters, and severity of MR.

Most patients supported by pulsatile LVADs have significant reductions in pulmonary pressures and TR (20,22). With continuous-flow pumps, higher pump speed settings can potentially increase the severity of TR because of increased RV preload (13) and distortion of the tricuspid valve annulus (mediated by shifting of the interventricular septum and subsequent papillary muscle distortion). Real-time echo can be used to adjust the pump speed setting (i.e., decrease the RPMs) to produce a more rightward shift of the interventricular septum and a decrease in the severity of TR (23).

In a normally functioning pulsatile pump, AV opening is infrequent (24). Aortic valve opening during continuous-flow LVAD support depends on the balance between native LV systolic function, the LVAD pump speed, the degree of LV unloading and preload and afterload pressures. Myers et al. (25) reported that the AV was open 97% of the time at a low Jarvik pump speed (8,000 RPM) compared with only 22% of the time at the highest pump speed. The clinical implications of reduced AV pulsatility or persistent AV closure are as follows: 1) automated blood pressure cuff measurements are unreliable given the decrease in pulse pressure within the arterial circulation; 2) aortic regurgitation (AR) may worsen and can be seen throughout the cardiac cycle; 3) complete AV closure has been associated with thrombus formation in the aortic root; and 4) complete AV closure at low pump settings may indicate a high level of LVAD dependency. The risk of developing AR is increased during LVAD support because the continuously closed AV is exposed to a higher pressure gradient (20). The incidence of AR after LVAD placement in patients without previous aortic insufficiency however is low (24). Both AV motion and AR can be analyzed by echo (Fig. 6). If clinically significant AR is suspected, it can be confirmed by observing reduced flows across the RV outflow tract despite normal inflow/outflow cannula Doppler profiles, in addition to significant regurgitation parameters by echo color Doppler.

Myocardial Recovery

The LVAD Working Group demonstrated that LVEF improved and LVEDd decreased early after LVAD implantation. After longer duration of LVAD support (4 months), recurrent LV dilation and a decline in LVEF was observed (5). Most patients, however, experienced an improvement in functional capacity despite seemingly adverse serial changes in LV size and contractility. Myocardial recovery, on the other hand, can occur in a small percentage of patients supported by LVADs (5% to 11%) (4,5). Data to assess the potential for recovery of function and possible LVAD explantation are, however, sparse. In the presence of signs of LV recovery, a clinical profile that may prompt consideration of possible elective LVAD explantation is that of younger age, shorter duration of heart failure, and nonischemic etiology (26,27).

Pharmacologic and exercise stress echo during off-pump, partial, and full LVAD support have been examined to detect recovery (Table 2) (3,5,26,27). The LVAD Working Group used dobutamine-stress echo to screen for recovery in patients with reduced LVAD support and an LVEF >40% (5). When cardiac recovery was defined by an LVEF >40% during exercise echo,

true long-term clinical stability was less likely as demonstrated in 2 reports where collectively 6 of 8 patients (75%) either died or developed recurrent heart failure after LVAD removal requiring LVAD reimplantation or HT within 3 years of follow-up (4,28). In contrast, Dandel et al. (26) demonstrated that the highest predictive off-pump resting echo values for long-term (≥3 years) post-LVAD cardiac stability were obtained for LVEF of ≥45% combined with either a LVEDd ≤55 mm or a relative wall thickness ≥0.38 (26). In this cohort, off-pump LVEF ≥40% alone showed low predictability for cardiac stability after LVAD removal. These data support the notion that measures of wall stress and LV size, in addition to LVEF, are important. Although there is no uniformly accepted LVAD echo weaning protocol, the decision for device explantation is usually based on clinical stability and invasive hemodynamics in addition to echo parameters of cardiac structure and function.

A novel surrogate of LV systolic performance in patients supported by LVADs is based on AV opening. LV contractility can increase over the course of LVAD support, with an associated increase in the frequency/duration of AV opening. Mancini et al. (4) used echo to quantitate AV opening in pulsatile LVADs at rest and at peak exercise. With reduced LVAD support in 18 patients evaluated for potential myocardial recovery, AV opening was present in almost all patients (4). In patients supported by continuous-flow devices, increasing device support can unload the LV to a point where LV systolic pressure is less than mean arterial pressure. This causes continuous AV closure. The speed setting at which this occurs is related in part to underlying LV contractility (29). The ability to maintain AV opening above relatively high levels of continuous pump support (i.e., HeartMate II [Thoratec Corp.] pump speed 10,000 RPM vs. 9,000 RPM) was noted in patients who had successful elective LVAD explantation (30). These retrospective observations are limited by small sample size. Additional studies are needed to incorporate AV opening/LV outflow tract flow assessment in addition to standard echo parameters to identify patients with sufficient LV recovery who benefit from elective LVAD explantation.

Lastly, there is a paucity of literature evaluating LV recovery in patients supported by continuous-flow pumps. Completely stopping or lowering rotor pump speed in these patients may lead to retrograde flow into the LV and influence the assessment of LV size and function. Therefore, the observation of reducing the pump speed to a rate where there is no forward or back flow through the inflow or outflow cannula (i.e., HeartMate II [Thoratec Corp.] pump speed 6,000 RPM) using Doppler echo may be similar to off-pump pulsatile, weaning LVAD echo studies (14,26,31). However, further prospective studies are needed.

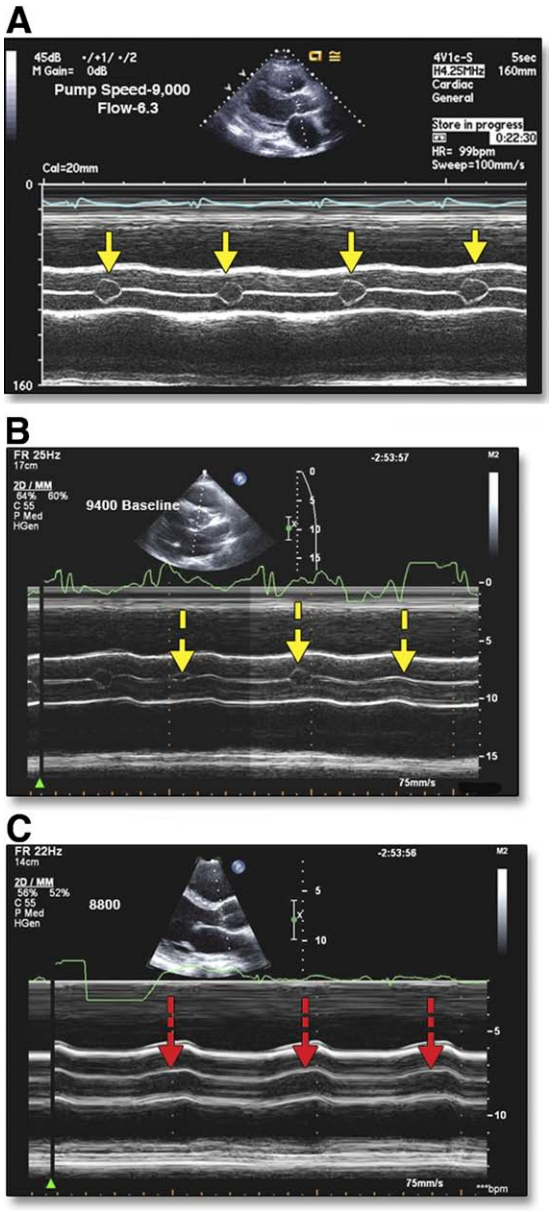


Figure 6. Various Degrees of Aortic Valve Opening With Continuous-Flow Support

M-mode illustration of various patterns of aortic valve opening **(arrows)** in 3 different patients with HeartMate II left ventricular assist devices (Thoratec Corp.). **(A)** Normal, consistent aortic valve opening. **(B)** Intermittent and variable partial aortic valve opening and closure. **(C)** Complete aortic valve closure (no opening).

Table 2. Examined Echo Parameters Associated With Myocardial Recovery

Author, Year (Ref. #)	Total Patients	LVAD Type	Echo Protocol	Echo Parameters of Patients Deemed Favorable Versus Unfavorable for LVAD Explant	p Value	Outcome Associated With Favorable Response
Khan et al., 2003 (3)	16	100% pulsatile pumps	Dobutamine stress echo*	LVEF: 48 ± 9% vs. 27 ± 11% LVEDd: 4.68 ± 1.1 cm vs. 5.48 ± 0.5 cm LVSD: 3.43 ±0.9 cm vs. 4.63 ± 0.6 cm	<0.01 0.3 <0.001	6 of 9 favorable responders survived more than 12 months following LVAD explant
Maybaum et al., 2007 (5)	15	98% pulsatile pumps	Dobutamine stress echo*	LVEF: 60 ± 10% vs. 40 ± 13%	0.05	6 favorable responders define the LVAD explant group
George et al., 2007 (27)	22	100% pulsatile pumps	Off-pump echo†	LVEF: 63.9 ± 6.9% vs. 30 ± 17.9% LVEDd: 5.65 ± 0.82 cm vs. 6.0 ± 1.05 cm LVSD: 4.0 ± 0.66 cm vs. 5.32 ± 1.23 cm	<0.05 NS <0.05	14 of 16 favorable responders demonstrated clinical stability following LVAD explant
Dandel et al., 2008 (26)	27	88% pulsatile pumps	Off-pump echo‡	LVEF: 48.9 ± 1.0% vs. 42.6 ± 1.6% LVEF: change: −4.2 ± 1.2% vs. −16.2 ± 4.5%§ LVEDd: 4.9 ± 1.1 cm vs. 5.6 ± 1.2 cm LVEDd change: 5.0 ± 1.5% vs. 19.9 ± 4.5%§ RWT: 0.41 ± 0.01 vs. 0.33 ± 0.01 RWT change: −7.1 ± 0.6 vs. −16.6 ± 2.0%‖ LV sphericity index: 0.65 ± 0.02 vs. 0.72 ± 0.02¶	<0.01 <0.001 <0.01 <0.001 <0.001 <0.001 0.04	15 favorable responders compared with 12 explanted nonresponders demonstrated clinical stability >5 years following LVAD explant

*Dobutamine stress echocardiography during LVAD weaning with echo parameters obtained at peak dobutamine. †Off-pump echo with parameters obtained 15 min after pneumatic hand pumping. ‡Off-pump echo with the maximum echo parameters obtained during repeated off-pump trials performed over several days. §LVEF and LVEDd change are the percentages of best value recorded during repeated-off pump trials. ‖RWT change is the percentage of change recorded during repeated off-pump trials. ¶LV sphericity index is defined as the LV short-/long-axis ratio.

LVEDd = left ventricular end-diastolic diameter; LVEF = left ventricular ejection fraction; LVSD = left ventricular end-systolic diameter; NS = not significant; RWT = relative wall thickness; other abbreviations as in Table 1.

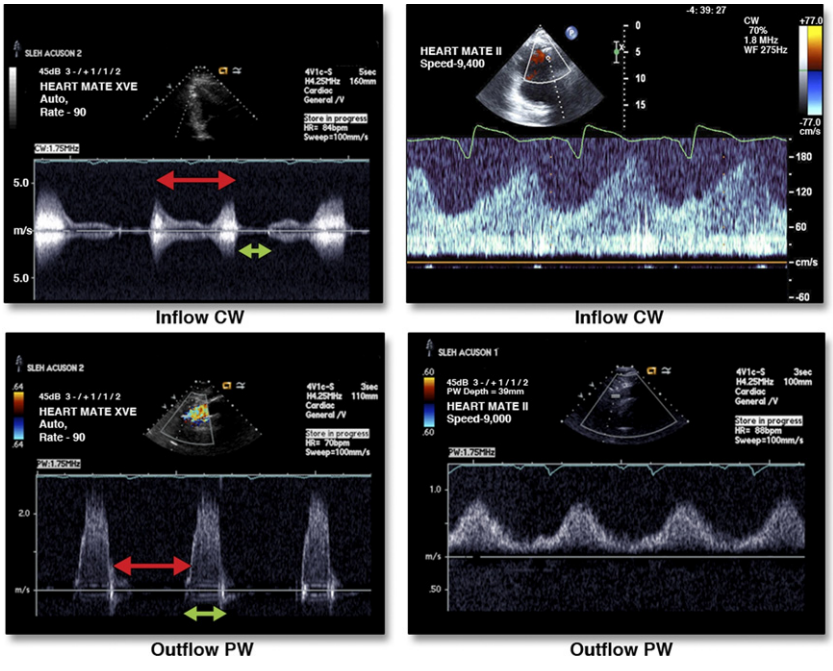


Figure 7. Spectral Doppler Examination of LVAD Cannulas

Illustration of normal inflow and outflow cannula velocity patterns for pulsatile and continuous flow left ventricular assist devices. **Red** and **green arrows** represent the pump-filling and ejection time periods, respectively. Standard apical (inflow) and right parasternal axis (outflow) views used. CW = continuous wave Doppler; PW = pulsed wave Doppler; other abbreviations as in Figure 1.

Detection of LVAD Dysfunction and Post-Implant Complications

Normal LVAD cannula Doppler findings. The inflow and outflow cannula and associated flows are always defined relative to the device. Apical inflow and outflow cannula position, flow type and direction, and the velocity flow pattern can be assessed using 2-dimensional, color and spectral Doppler echo in the majority of cases. Horton et al. (24) demonstrated that the inflow cannula can be imaged from the apical views in 96% and the outflow conduit from the right parasternal view in 98% of transthoracic echos. In our experience, these can be imaged in the vast majority (~80%) of cases using standard and off-axis views. For pulsatile LVADs, peak apical inflow velocities are usually below 2.5 m/s with a peak outflow cannula velocity ~2 m/s (22,24). In comparison, continuous-flow LVADs have normal, consistently phasic, slightly pulsatile, low-velocity inflow and outflow patterns, with peak velocities <2.0 m/s and typically <1.5 m/s (Fig. 7) (13,32). Normal apical inflow appears as nonturbulent flow toward the apical transthoracic transducer. However, with off-axis imaging, the apparent direction of normal flow relative to the transducer may vary (Fig. 8).

Abnormal LVAD cannula Doppler findings. LVAD dysfunction may be indicated by built-in alarm systems that sense low pump rates caused by various mechanisms of cannula obstruction. These include: cannula thrombus, partial inlet occlusion by adjacent myocardial trabeculations, cannula angulation into the myocardium or other cannula malposition caused by LV underfilling, and inlet or outlet kinking (23,33). For pulsatile pumps, a peak inflow

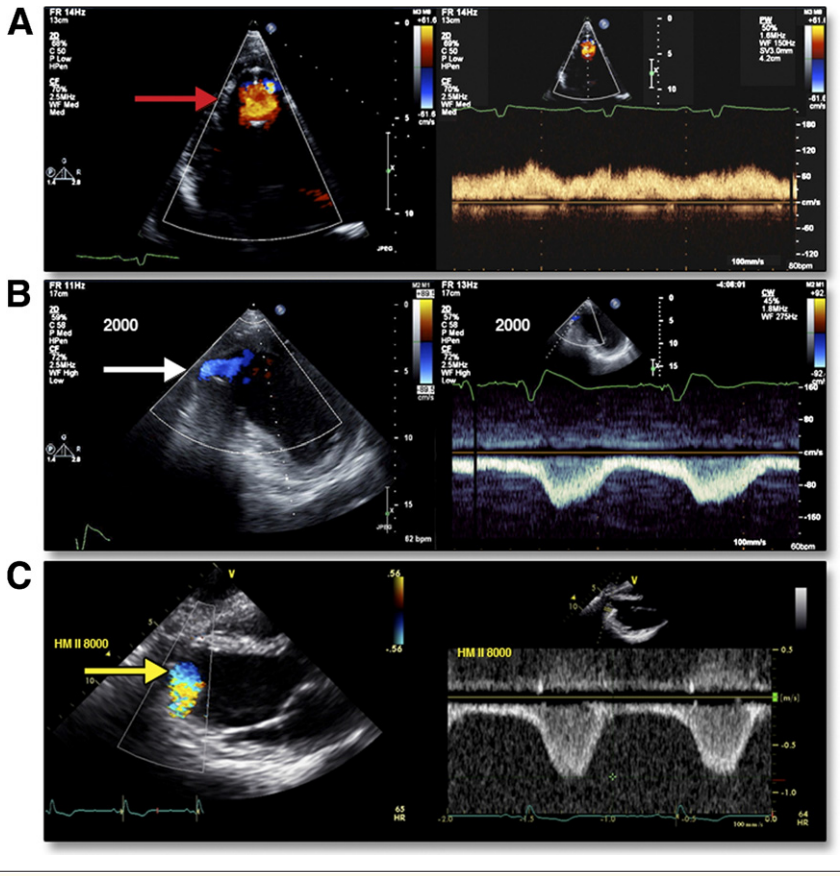


Figure 8. Effect of Imaging Windows on Doppler Recordings of the Apical Inflow Cannula

Normal continuous left ventricular assist device apical inflow Doppler optimized for window of acquisition in 3 different patients. **(A)** Standard 4-chamber apical view with nonaliasing color Doppler apical inflow **(red arrow)** and low peak velocity (<1.5 m/s) with flow directed toward the apical transducer. **(B)** Off-axis 2-chamber apical view illustration of normal apical inflow characteristics **(white arrow)**. Note the Doppler signal directed away from the transducer with normal flow relative to the device. **(C)** Parasternal long-axis view illustration of normal apical inflow **(yellow arrow)**, similar to **B**.

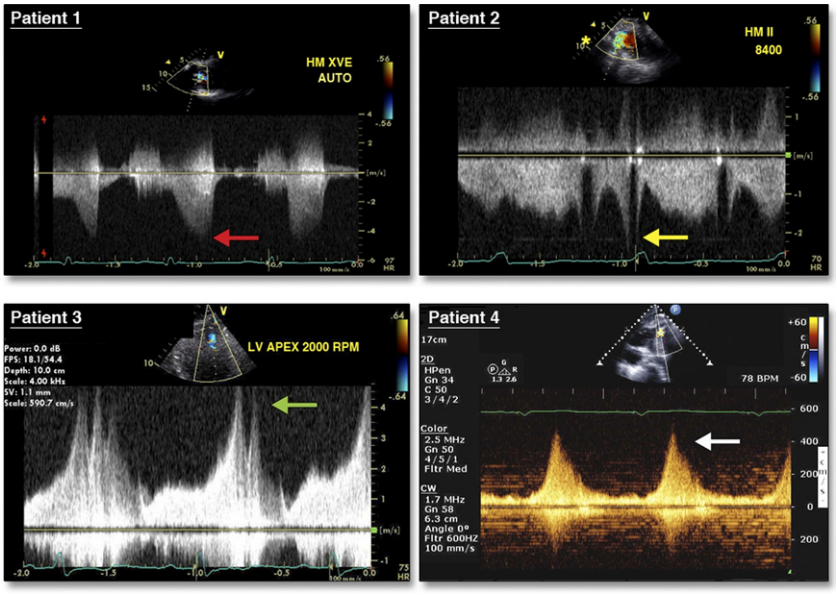


Figure 9. Examples of Apical Inflow Abnormalities Detected by Transthoracic Echo

Patient #1: HeartMate XVE (Thoratec Corp.) inflow cannula obstruction from malposition. Modified apical parasternal long-axis view with elevated continuous wave Doppler peak device filling velocity ~4 m/s **(red arrow)** (normally <2.5 m/s). Patient #2: HeartMate II (Thoratec Corp.) dynamic inflow cannula obstruction due to overly decompressed left ventricle with septum abutting device inflow. Modified apical parasternal long-axis view with turbulent flow **(yellow *)** and continuous wave Doppler peak inflow velocity intermittently approaching 2 m/s. Patient #3: VentrAssist (Ventracor) inflow cannula obstruction from malposition (Fig. 12). Apical view with increased continuous wave Doppler peak inflow velocities >4 m/s **(green arrow)**. Patient #4: HeartMate II (Thoratec Corp.) hyperdynamic left ventricular ejection into the device after myocardial recovery. Off-axis apical view with continuous wave Doppler peak inflow velocity ~4 m/s **(white arrow)**. LV = left ventricular; other abbreviations as in Figure 4.

velocity >2.5 m/s or intermittent interruptions of the usual laminar cannula inflow is indicative of inflow cannula obstruction (22,24). In contrast, for continuous-flow pumps, a peak inflow velocity >2 m/s with associated turbulent flow may represent either inflow cannula obstruction, malposition, or improved LV systolic function (Fig. 9) (32,33). For pulsatile LVADs, significant inflow valve regurgitation secondary to mechanical failure of the inflow valve is the most common cause of LVAD dysfunction (Fig. 10). Horton et al. (24) demonstrated that a peak outflow velocity ≤1.8 m/s is associated with an 84% specificity and 89% sensitivity to detect significant inflow valve regurgitation. Because continuous-flow LVADs are valveless, diastolic regurgitation through the outflow graft from the aorta into the LV secondary to pump failure is associated with an abnormal retrograde apical flow pattern (Fig. 11).

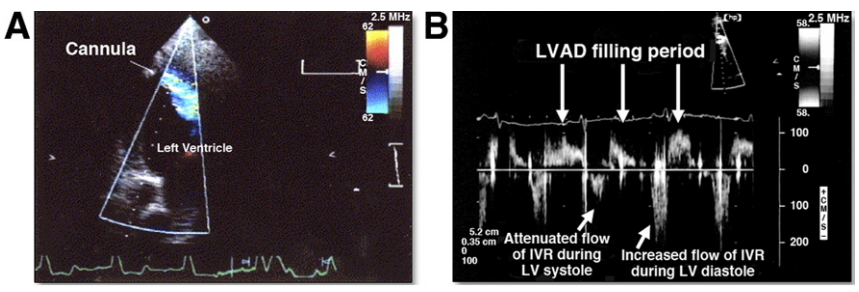


Figure 10. Detection of Inflow Valve Regurgitation

(A) Color Doppler showing inflow valve regurgitation. **(B)** Pulsed Doppler showing attenuation of inflow valve regurgitation flow during left ventricular systole and increased flow during left ventricular diastole. Adapted, with permission, from Horton et al. (24). IVR = inflow valve regurgitation; other abbreviations as in Figure 9.

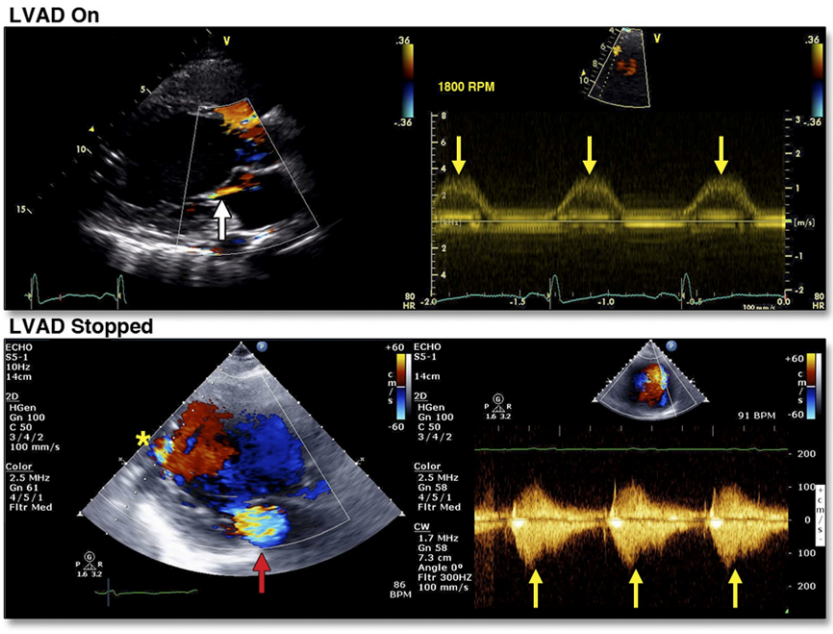


Figure 11. Echo Findings With Continuous-Flow Pump Failure

Left ventricular assist device on: Parasternal long-axis view with minimal mitral regurgitation **(white arrow)** and a normal apical inflow velocity flow pattern **(yellow arrows)**. Left ventricular assist device stopped: 2 months later, VentrAssist (Ventracor) pump failure with regurgitant inflow **(yellow *)**, increased mitral regurgitation **(red arrow)**, and reversal of apical inflow **(yellow arrows)** using spectral Doppler standard apical view. Abbreviations as in Figure 4.

Other LVAD dysfunction/related complications. In addition to thrombosis of the LVAD cannula, several other complications may occur early and late after implantation that can be detected by echo and are listed in Table 3. Cannula malposition may cause low-flow LVAD alarms, ventricular arrhythmias, or a clinically low CO state. Increasingly, with newer third-generation device shapes or because of specific body habitus, the inflow cannula may be placed in an inferior LV approach. This may necessitate modified 2-dimensional and Doppler imaging from the parasternal views as opposed to the apical view. Cannula/graft malposition or distortion may also be suspected on routine chest radiography or detected by

Table 3. LVAD Dysfunction and Post-Implant Complications Detected by Echo

Pericardial effusion with or without cardiac tamponade
RV failure (increased RV size, decreased RV systolic function, increased right atrial pressure, and increased tricuspid regurgitation)
Inadequate LV filling (small LV dimensions)
LVAD-induced ventricular ectopy or tachycardia (underfilled LV and mechanical impact with septum)
LVAD-related continuous aortic insufficiency (aortic regurgitation throughout cardiac diastole and systole)
Intracardiac thrombus (including right and left atrial, LV apical, and aortic root thrombus)
Pulsatile pump inflow valve regurgitation (apical inflow cannula turbulent flow detected by color Doppler during LVAD ejection, dilated LV, frequent opening of the AV, and reduced outflow graft flow $<$1.8 m/s)
Pulsatile pump apical inflow obstruction (intermittent interruption of usual laminar LVAD diastolic inflow using pulsed-wave Doppler with inflow velocities $>$2.5 m/s and color flow aliasing at the cannula orifice)
Continuous pump apical inflow abnormality due to inflow cannula obstruction, malposition, or hyperdynamic apical LV function (color Doppler high-velocity aliased flow at the cannula orifice with a peak Doppler velocity $\geq$2 m/s)
Cannula kinking or complete thrombosis (loss of Doppler signal in all echo views and loss of RV outflow tract stroke volume with speed change)
Hypertensive emergency, continuous flow pump (minimal AV opening, dilated LV, worsening MR, and peak outflow cannula velocity $>$2 m/s)
Impeller cessation, continuous flow pump (dilated LV, acute reversal of apical inflow flow direction using spectral or color Doppler, worsening MR, and decreased RV outflow tract stroke volume)

AV = aortic valve; LV = left ventricle; MR = mitral regurgitation; RV = right ventricle; other abbreviations as in Table 1.

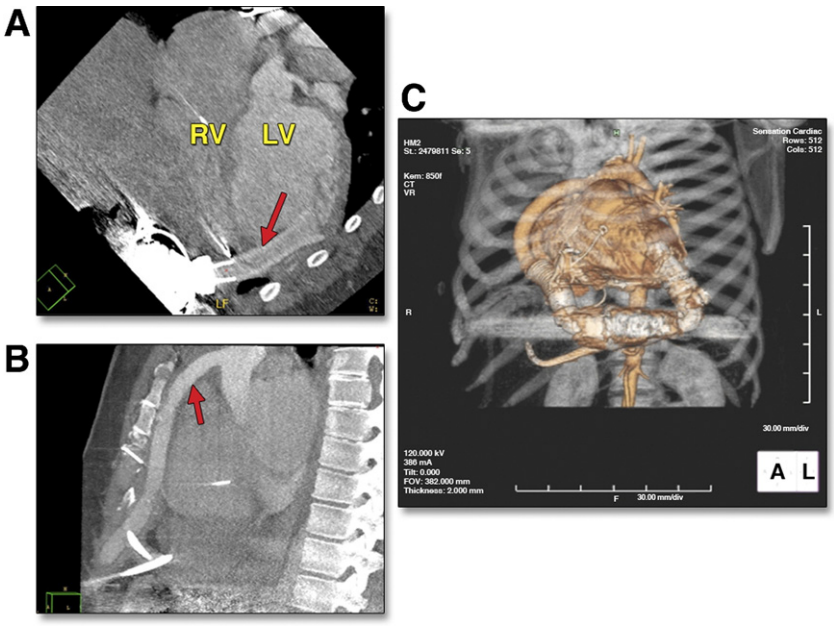


Figure 12. Cardiac CT Illustration of LVAD

(A) VentrAssist (Ventracor) apical inflow cannula visualization (malposition with the cannula directed toward the distal left ventricular free wall with no apical inflow thrombus seen). Note the nonmetallic inflow cannula extension **(red arrow). (B)** Contrast computed tomography showing a patent, nonobstructed outflow cannula/graft **(red arrow)**. Courtesy of Su Min Chang, MD. **(C)** Three-dimensional volume rendering of contrast-enhanced electrocardiograph-gated cardiac computed tomography demonstrating both the HeartMate II inflow and outflow cannulas. By multiplanar reformation (not shown), the inflow cannula is directed toward the distal interventricular septum. See Online Video 1. Courtesy of Benjamin Y. Cheong, MD. CT = computed tomography; RV = right ventricle; other abbreviations as in Figures 1 and 9.

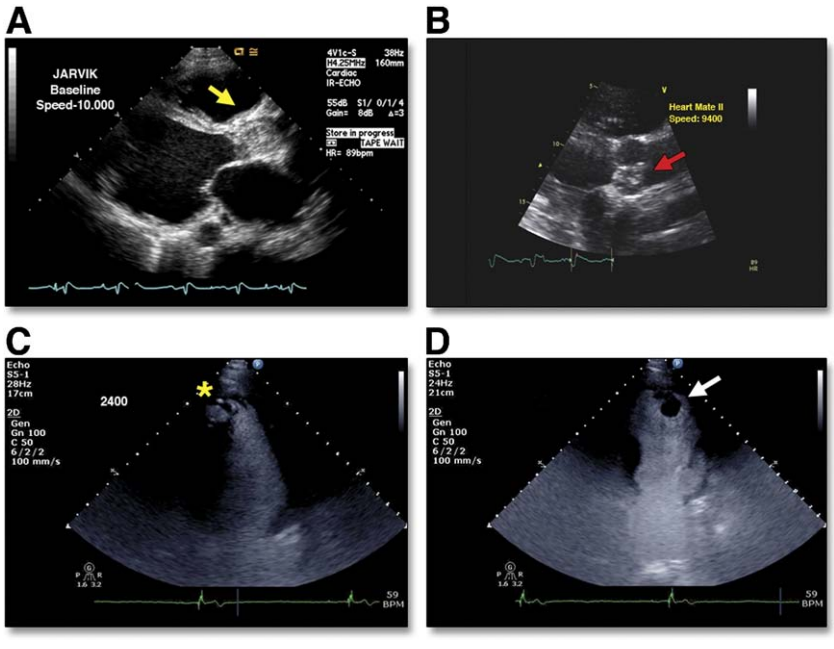


Figure 13. Echo Detection of Thrombus in Patients With Continuous-Flow LVADs

(A) Aortic root thrombus **(yellow arrow)**. **(B)** Coronary cusp thrombus **(red arrow)**. **(C)** Visualized apical inflow cannula **(yellow *)** using contrast echo. **(D)** Apical thrombus **(white arrow)** seen with contrast echo adjacent to but not obstructing the inflow cannula. Abbreviations as in Figure 1.

catheter-based techniques (34). A potentially robust imaging modality to image LVAD cannulas is cardiac CT. In comparison to echo, cardiac CT is not limited by acoustic windows and lacks acoustic shadowing. Furthermore, the LVAD cannulas can be interrogated from multiple views, permitting direct visualization (Fig. 12). Raman et al. (35) demonstrated that the sensitivity and specificity of cardiac CT to detect cannula thrombosis or inflow cannula malposition using intraoperative findings as the gold standard was 85% and 100%, respectively. A limitation of cardiac CT, however, relates to the radiation exposure and the risk of nephrotoxicity from iodinated contrast.

Rarely, LVAD support is associated with aortic root thrombosis secondary to blood stasis in the setting of prolonged AV closure. In persistent closed AVs, laminated thrombus may form more commonly or more prominently in the noncoronary cusp, presumably due to lack of coronary artery runoff. Thrombus can also form in the cardiac apex. Echo, especially with the use of contrast, can aid in the identification of apical thrombus, which can be difficult to detect in the presence of an apical inflow cannula (Fig. 13). Echo can also identify circulating air microcavitations. Pulsatile pumps may produce negative inflow pressures when functioning in a low pressure environment, such as systemic hypotension in the operating room, or after placement of the inflow cannula in the left atrium (36,37). A small leak in the negative pressure circuit exposed to air may produce catastrophic air embolism, which can be detected by ultrasound.

Both pulsatile and continuous flow LVADs have been associated with commissural fusion of the AV (38,39). Although the true incidence of AV commissural fusion and its determining factors are unknown, a recent study has suggested that AV commissural fusion may be related to the presence of mild-to-moderate continuous AR (Fig. 14) (39). Other complications include kinking, thrombus, or endocarditis at the outflow cannula–ascending aorta anastomotic site. A modified parasternal transthoracic echo approach can often follow the course of the outlet conduit up the anterior chest to the level of the aortic anastomosis as well, serving as a routine LVAD view (Fig. 15A). Transesophageal echo may be useful in visualizing this area from the transverse aorta level or through the level of the right pulmonary artery (Fig. 15B). Transesophageal echo can also be used in critically ill patients in the intensive care units, when an atrial level right-to-left shunt or a cardiac source of embolus following LVAD is suspected.

Imaging artifacts. As previously alluded to, the inflow cannula produces a characteristic downfield signal attenuation artifact that can hamper endocardial definition. Doppler artifacts seem to be related to the proximity of the moving impeller mechanism to the inflow cannula. Such devices include the Jarvik

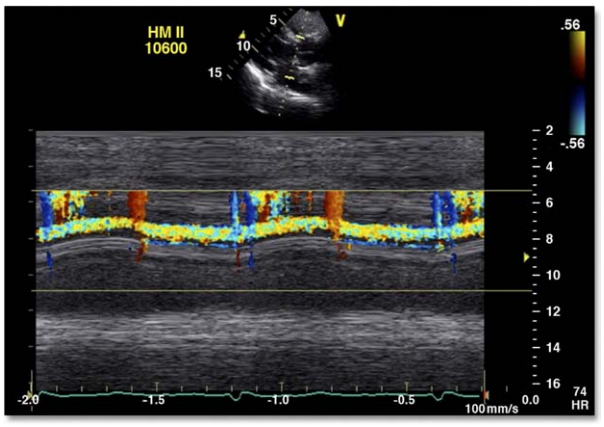


Figure 14. LVAD-Associated Continuous Aortic Regurgitation

Color M-mode illustrating continuous aortic regurgitation (seen throughout systole and diastole). See Online Video 2. Abbreviation as in Figure 1.

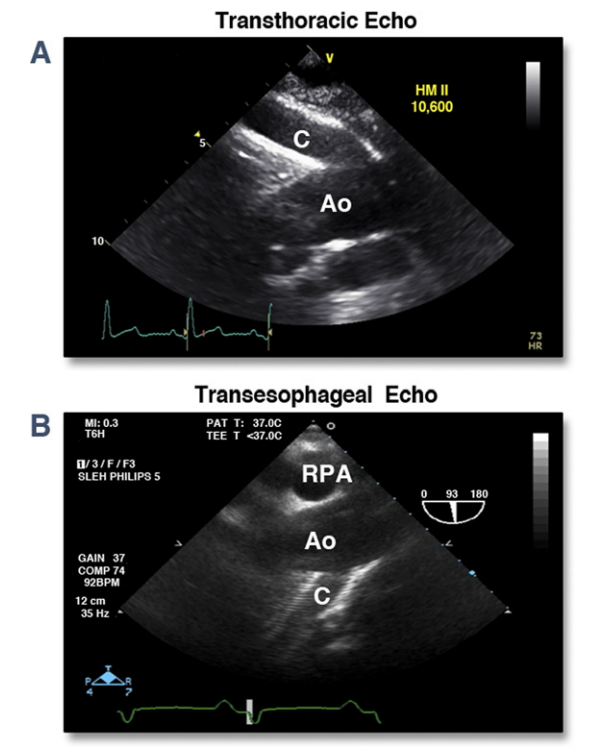


Figure 15. Outflow Cannula Visualization by 2-Dimensional Echo

Transthoracic echo using the low right parasternal view **(A)** and transesophageal echo **(B)** at the level of the right pulmonary artery to visualize the outflow cannula. Ao = ascending aorta; C = outflow cannula; RPA = right pulmonary artery.

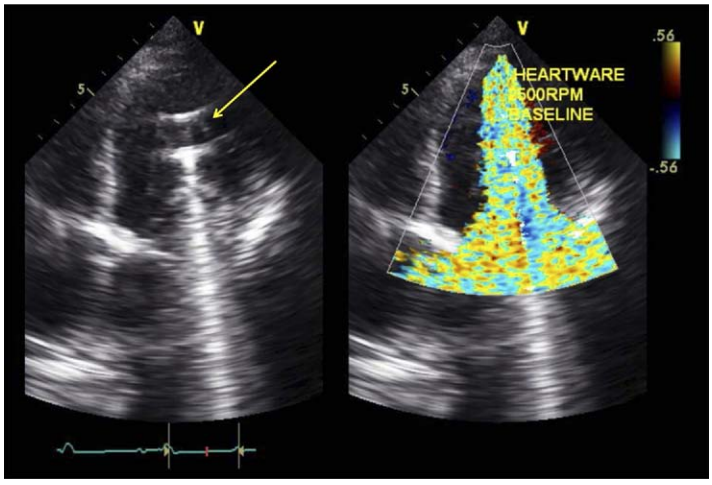


Figure 16. Imaging Artifact With Newer Continuous-Flow Devices

Extensive color Doppler artifact when the color sector included the HeartWare apical inflow cannula (**yellow arrow**).

LVAD (Jarvik Heart Inc., New York, New York), an impeller mechanism intrinsic to the inlet cannula, and the DuraHeart (Terumo Heart Inc., Ann Arbor, Michigan) and HeartWare (HeartWare Inc., Framingham, Massachusetts), centrifugal pump housings that come in contact with inflow cannula. When the inflow cannula is within the imaging sector, Doppler signals are severely degraded, presumably due to the production of ultrasound frequencies from the device (Fig. 16). However, in most cases, this can be "worked around" by modified views to exclude actual images of the inflow cannula.

Imaging acquisition/reporting. In our practice, the comprehensive LVAD exam consists of a standard echo with attention to ventricular dimensions, AV function, and routine inflow and outflow cannula interrogation as noted in Table 4. We obtain a baseline surveillance transthoracic echo 2 weeks after implant then routinely every 3 to 6 months and as clinically indicated. If the echo is technically difficult despite echo contrast use, transesophageal echo is usually performed when LVAD dysfunction is suspected or in the presence of complications. Cardiac CT can be employed if there is persistent clinical concern for inflow/outflow graft thrombosis or malposition in the setting of a nondiagnostic echo.

Conclusions

Echocardiography is the primary imaging modality to determine ventricular size and function, assess valvular function, and screen for pulmonary hypertension and myocardial recovery in patients supported by LVADs. Knowledge of LVAD physiology, its effect on cardiac function, and potential complications is essential. In comparison to echo, cardiac CT offers complete visualization of the inflow and outflow cannulas and anastomotic sites and can be helpful in detecting device-related thrombus, kinking, or malposition. We have described the application of echo for surgically placed adult LVADs, and many of the same concepts apply to percutaneous continuous-flow and pediatric LVADs. As newer generation continuous-flow LVADs gain widespread recognition with more long-term support anticipated, standardized echo image acquisition, interpretation, and potentially multimodality imaging will aid researchers and clinicians to study, monitor, and care for this increasing patient population.

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Table 4. LVAD Echo Imaging and Reporting Protocol

1. Document standard demographics, annotate device type, device mode or pump speed setting (i.e., RPMs for continuous-flow pumps; automatic or fixed rate for pulsatile pumps).
2. Standard comprehensive echo examination for any heart failure patient.
3. Parasternal long- and short-axis views: record 3 to 5 cardiac cycles, 2D and M-mode evaluation to assess ventricular dimensions/function and qualitative AV opening frequency/duration.
4. Inflow cannula views (orientation can vary): use standard and off-axis 4- and 2-chamber apical views, parasternal long- (mid level) and apical parasternal long-axis views (modified apical). Obtain 2D, color, and spectral Doppler from view with the best alignment. Report flow characteristics (flow direction, turbulent versus nonturbulent flow and peak velocity) to delineate normal from an obstructive or a reversal flow pattern.
5. Outflow cannula views: right parasternal (low- and mid-level) view. Obtain 2D, color, and spectral Doppler and report flow characteristics similar to the inflow examination.
6. Outflow cannula-ascending aorta anastomosis view: right parasternal (low, mid, or higher level) view or sternal notch view. Obtain 2D, color, and spectral Doppler.

2D = 2-dimensional; RPM = revolutions/min; other abbreviations as in Tables 1 and 3.

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Key Words: cardiac computed tomography ■ echocardiography ■ left ventricular assist device ■ myocardial recovery.

APPENDIX

For supplementary videos and their legends, please see the online version of this article.