Echocardiography and Continuous-Flow Left Ventricular Assist Devices
Evidence and Limitations

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ABSTRACT

Echocardiography is the most used imaging modality in the growing population of patients with advanced heart failure undergoing continuous-flow, durable mechanical circulatory support. However, no guidelines for the use of echocardiography in this population exist, evidence for core applications is limited and conflicting, and newer centrifugal-flow devices have been subject to minimal study. As a first step toward addressing these deficits, this review summarizes the evidence and expert opinion for the use of echocardiography in pre-operative planning and perioperative management, prediction of post-operative right ventricular failure, the use of echocardiographic surrogates for invasive hemodynamic measurements, and the performance of speed ramp studies for the diagnosis of thrombosis and optimization of device settings. (J Am Coll Cardiol HF 2015;3:554–64) © 2015 by the American College of Cardiology Foundation.

Mechanical circulatory support for advanced heart failure has evolved from its origins in bulky extracorporeal machines used for days to weeks in intensive care units, to implantable pumps intended for months of waiting on the transplantation list, to durable devices designed for permanent use (1,2). Continuous-flow left ventricular (LV) assist devices (LVADs) have almost entirely supplanted earlier pulsatile flow devices, and destination therapy—the long-term use of durable mechanical circulatory support (DMCS) in patients for whom heart transplantation is not appropriate—is on track to become the dominant indication (3). The DMCS-supported population is growing rapidly, patients are living longer with their LVADs, the number of centers offering DMCS is growing, and the diversity of commercially available devices is expected to expand. Cardiac imaging is an indispensable tool to optimize pump performance and ensure successful outcomes. Consequently, there is a real need for standardized, evidence-based cardiac imaging to guide decision making in LVAD-supported patients.

Echocardiography is the most used imaging modality in patients with advanced heart failure undergoing DMCS (4,5). Echocardiography is portable, noninvasive, and inexpensive; involves no exposure to radiation or nephrotoxic contrast agents; and, unlike cardiac magnetic resonance imaging, can be performed in the presence of LVAD support.

The International Society for Heart and Lung Transplantation recommends the use of echocardiography for pre-operative assessment, routine follow-up, and evaluation of circulatory dysfunction in DMCS patients (6). However, guidelines for the use of echocardiography in the DMCS population do not currently exist. In the absence of such standardization, the use of echocardiography varies widely among centers, with differing degrees of comfort and sophistication. Technical issues pertaining to image acquisition pose only 1 barrier to the optimal use of echocardiography in DMCS patients. Other
fundamental issues include the limited and often conflicting evidence basis for core applications such as the prediction of post-operative right ventricular (RV) failure, the use of echocardiographic surrogates for invasive hemodynamic measurements, and the performance of speed ramp studies for the diagnosis of thrombosis and optimization of device settings (Central Illustration). Of critical importance, the overwhelming majority of evidence for the use of echocardiography in DMCS patients is derived from experience with axial-flow LVADs (Table 1). Centrifugal-flow devices are being implanted with increasing regularity, posing unique challenges to image acquisition and necessitating independent validation.

It should be noted that a growing variety of continuous-flow devices are available for the temporary circulatory support of patients with cardiogenic shock. The role of echocardiography in managing such temporary assist devices is outside the scope of this review. It should also be noted that this review is not intended to be a “how-to” guide for using echocardiography in LVAD-supported patients with heart failure. Rather, as a first step toward eventual protocol standardization, we summarize the available evidence for the use of echocardiography in continuous-flow DMCS, highlighting both its utility and limitations as a tool for pre-operative evaluation, perioperative assessment, longitudinal follow-up, diagnosis of complications, and speed optimization. We conclude by highlighting opportunities for systematic investigation and further standardization.

**PRE-OPERATIVE EVALUATION**

**OPERATIVE PLANNING.** In addition to documenting baseline cardiac structure and function, pre-operative echocardiography is vital for surgical planning (Table 2). Aortic insufficiency (AI) tends to worsen after LVAD implantation (7–9), and the presence of moderate or greater AI is typically an indication for valve replacement or oversizing at the time of surgery (6). Although tricuspid regurgitation (TR) might be expected to improve with reduction in pulmonary vascular resistance after LVAD placement, the increase in RV preload and subsequent distortion of RV and septal geometry may actually worsen tricuspid regurgitant flow (4). Moderate to severe TR should therefore be considered for repair or replacement, although surgical intervention at the time of implantation remains a debated practice (6,10). Although a stenotic mitral valve should be addressed at implantation, repair of even a severely regurgitant mitral valve is rarely indicated, as functional regurgitation usually diminishes considerably with mechanical unloading of the left ventricle (5,6).

The fall in left atrial pressure and increase in right atrial pressure after LVAD placement may exacerbate a right-to-left atrial shunt, resulting in hypoxemia and raising the risk for paradoxical embolus (5,11). Meticulous assessment for a patent foramen ovale or an atrial septal defect with both color Doppler and agitated saline contrast should be performed (6) and repeated in the operating room at the time of implantation (11).

**RISK STRATIFICATION FOR RV FAILURE.** RV failure remains one of the most ominous complications after LVAD placement, resulting in substantial morbidity and mortality (12–14). The reported incidence is widely variable but clinically significant in all cohorts, ranging from 13% to 40% (15). Pre-operative risk stratification is important not only for its prognostic value to patients and physicians but also for its potential to alter surgical strategy, because planned biventricular support is associated with better in-hospital and 1-year mortality than delayed conversion (16).

Post-LVAD RV failure is poorly understood but is hypothesized to derive in part from geometric changes that occur with increased RV preload and leftward shift of the interventricular septum (12,13,15), making echocardiography a practical tool for risk stratification. Unfortunately, the use of standard quantitative echocardiographic predictors of RV failure in this population is limited by conflicting evidence (Table 3). Furthermore, definitions of RV failure vary among these studies.

Given the limited reproducibility of standard echocardiographic techniques, attention has turned to more novel techniques, including tissue Doppler and strain imaging. Both have shown promise, though evidence remains limited (Table 3). Although tissue Doppler circumvents the need for comprehensive views of the right ventricle, it is dependent on the angle of the transducer, can be confounded by cardiac motion (17), and may understate myocardial performance because of tethering by adjacent hypokinetic segments or adherent scarred pericardium (15).

Strain imaging by speckle-tracking echocardiography, a sensitive method for quantifying myocardial deformation, is less dependent on insonation angle than tissue Doppler (17) and less affected by regional hypokinesis (15). As with all echocardiographic methods of quantifying RV function, RV strain imaging requires adequate views of the right ventricle.

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**ABBREVIATIONS AND ACRONYMS**

AI = aortic insufficiency
DMCS = durable mechanical circulatory support
LV = left ventricular
LVAD = left ventricular assist device
LVEDD = left ventricular end-diastolic diameter
MR = mitral regurgitation
PCWP = pulmonary capillary wedge pressure
RV = right ventricular
TEE = transesophageal echocardiography
TR = tricuspid regurgitation
TTE = transthoracic echocardiography
In addition, there are limited data on inter-vendor reproducibility and test-retest variability (19).

PERI-OPERATIVE ASSESSMENT

Intraoperative transesophageal echocardiography (TEE) is vital to successful LVAD placement (6). However, clinical practice is shaped largely by anecdote, local practice patterns, case reports, and small series. The available body of research, consisting mostly of expert opinion, is summarized here.

Comprehensive TEE should be performed before placing the patient on cardiopulmonary bypass. Particular attention should be paid to RV function,
valvular disease (including AI, previously underappreciated TR, mitral stenosis, and pulmonary stenosis), intracardiac shunt, intracardiac thrombus, and disease of the ascending aortic (atheroma, aneurysm, and dissection) (11,20,21).

During LVAD implantation, TEE should be used to confirm inflow cannula placement, ruling out inadvertent angulation toward the septum or lateral wall. After device activation, Doppler should be used to assess for high-velocity (>2.0 m/s) or turbulent flow in the inflow cannula, which may indicate device thrombus or malposition of the cannula against the ventricular wall (11,20–22).

Separation from cardiopulmonary bypass marks a critical point in LVAD implantation. Before removal of bypass, TEE should be used to assess for adequate “de-airing” of the cardiac chambers, reducing the risk for stroke or right coronary artery ischemia from air embolism (11,20,21). After device activation, color Doppler and agitated saline contrast should be considered to assess for a patent foramen ovale unmasked by the fall in left atrial pressure (11). In addition, color Doppler should be used to examine the aortic valve for new or worsening regurgitation and the outflow cannula anastomosis for kinking (20).

Elevated central venous pressure and low cardiac output after device activation should prompt repeat TEE to investigate RV size and systolic function (12,13). A dilated right ventricle and leftward interventricular septal shift may suggest RV dysfunction, and once device malfunction has been ruled out, temporary or durable RV assist device placement should be considered (12,20). Patients with marginal RV function may benefit from conservative fluid management, aggressive inotrope and pulmonary vasodilator therapy (20), and an initial “partial unloading” strategy with low pump speed to avoid progression to frank RV failure (13). TEE can also be used to help determine initial pump speed, targeting a midline interventricular septal position (11).

Post-operative cardiac tamponade from hemopericardium (Figure 1, Online Videos 1 and 2) can be challenging to diagnose, as hemodynamically significant effusions may be small or loculated, device artifacts may impair Doppler examination, and physiologic changes with mechanical circulatory support may render traditional hemodynamic and echocardiographic markers unreliable (23,24).

### Longitudinal Follow-up and Noninvasive Hemodynamic Measurements

Continuous-flow LVAD support provides mechanical unloading of the left ventricle, with longitudinal transthoracic echocardiography (TTE) demonstrating reduced LV dimensions (9,25–30) and decreased mitral regurgitation (MR) (9,25,26,28), and with invasive hemodynamic measurements showing reduction in LV filling pressures (27,28,30,31). Diastolic phonoechocardiography can be used to identify mid-diastolic mitral valve closure for optimal timing ofanka.

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**TABLE 1 Evidence for Echocardiography in Continuous-Flow DMCS**

<table>
<thead>
<tr>
<th>Research Focus</th>
<th>HeartMate II</th>
<th>HeartWare HVAD</th>
<th>Other Device</th>
<th>Total</th>
<th>Ref. #s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prediction of RV failure</td>
<td>309 (78%)</td>
<td>8 (2%)</td>
<td>81 (20%)†</td>
<td>398</td>
<td>(63–70)</td>
</tr>
<tr>
<td>Longitudinal follow-up and myocardial recovery</td>
<td>622 (98%)</td>
<td>7 (1%)</td>
<td>6 (1%)</td>
<td>635</td>
<td>(9,25–31,33,43,44)</td>
</tr>
<tr>
<td>Validation of invasive hemodynamic measurements</td>
<td>70 (100%)</td>
<td>0</td>
<td>0</td>
<td>70</td>
<td>(36,45,46)</td>
</tr>
<tr>
<td>Diagnosis of pump thrombosis</td>
<td>128 (100%)</td>
<td>0</td>
<td>0</td>
<td>128</td>
<td>(55,56,59)</td>
</tr>
<tr>
<td>Speed optimization</td>
<td>28 (65%)</td>
<td>15 (35%)</td>
<td>0</td>
<td>43</td>
<td>(55,58)</td>
</tr>
<tr>
<td>Total</td>
<td>1,157 (91%)</td>
<td>30 (2%)</td>
<td>87 (7%)</td>
<td>1,274</td>
<td></td>
</tr>
</tbody>
</table>

Values are n (% of total). *Excludes sources that provide no information on device type beyond classi-

fication as continuous flow (34,68–70). †Yama et al. (63) included 32 HeartMate II, 6 HeartWare HVAD, and 1 unspecified continuous-flow device. Kukucka et al. (66) included 51 HeartMate II, 56 Berlin Heart Incor, 5 DuraHeart, 2 Jarvik 2000, 1 VentraAssist, and 1 MicroMed DeBakey LVAD. Viva et al. (67) included 93 HeartMate II and 16 other continuous-flow devices, including MicroMed DeBakey, VentraAssist, and DuraHeart, with numbers of each unspecified. Y’ama et al. (29) included 6 EVAHEART devices.

DMCS = durable mechanical circulatory support; LVAD = left ventricular assist device; RV = right ventricular.

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**TABLE 2 Management of Pre-Operative Echocardiographic Abnormalities in LVAD Candidates**

<table>
<thead>
<tr>
<th>Abnormality</th>
<th>Intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aortic insufficiency</td>
<td>Repair, replace, or oversew</td>
</tr>
<tr>
<td>Tricuspid regurgitation</td>
<td>Controversial; consider repair or annuloplasty if moderate to severe</td>
</tr>
<tr>
<td>Mitral stenosis</td>
<td>Valvotomy</td>
</tr>
<tr>
<td>Mitral regurgitation</td>
<td>Usually none if not organic</td>
</tr>
<tr>
<td>Patent foramen ovale or atrial septal defect</td>
<td>Repair</td>
</tr>
<tr>
<td>Aortic root dilation or atheroma</td>
<td>Consider alteration in outflow cannula placement</td>
</tr>
<tr>
<td>Intracardiac thrombus</td>
<td>Consider surgical thrombectomy</td>
</tr>
<tr>
<td>Severe right ventricular dysfunction</td>
<td>Consider short-term RVAD or durable BIVAD</td>
</tr>
</tbody>
</table>

BIVAD = biventricular assist device; LVAD = left ventricular assist device; RVAD = right ventricular assist device.
TABLE 3  Candidate Echocardiographic Predictors of Post-LVAD RV Failure

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ref. #s</th>
<th>Predictive</th>
<th>Not Predictive</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>RV fractional area change</td>
<td>(63)</td>
<td>(64,65,67-69)</td>
<td></td>
<td>Poor reproducibility</td>
</tr>
<tr>
<td><strong>RV/LV end-diastolic diameter ratio</strong></td>
<td>(66,67)</td>
<td>(65,70)</td>
<td></td>
<td>Standardization of views</td>
</tr>
<tr>
<td>TAPSE</td>
<td>(64,68,69)</td>
<td>(63,65-67,70)</td>
<td></td>
<td>Sensitive to afterload</td>
</tr>
<tr>
<td><strong>Tissue Doppler</strong></td>
<td>(64,68,69)</td>
<td>(63,65-67,70)</td>
<td></td>
<td>Less reliable if prior cardiac surgery</td>
</tr>
<tr>
<td>Tricuspid S’</td>
<td>(68,69)</td>
<td>(67)</td>
<td></td>
<td>Dependent on transducer angle</td>
</tr>
<tr>
<td>Tricuspid e’</td>
<td>(68)</td>
<td>–</td>
<td></td>
<td>Confounded by cardiac motion and tethering</td>
</tr>
<tr>
<td>RV strain</td>
<td></td>
<td></td>
<td></td>
<td>Limited validation of intervendor and test-retest reliability</td>
</tr>
<tr>
<td>Global longitudinal</td>
<td>(68)</td>
<td>–</td>
<td></td>
<td>Requires adequate views of RV free wall</td>
</tr>
<tr>
<td>Free wall longitudinal</td>
<td>(65)</td>
<td>–</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global systolic strain rate</td>
<td>(69)</td>
<td>–</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

E’ = early diastolic velocity of the tricuspid annulus; LV = left ventricular; LVAD = left ventricular assist device; PVR = pulmonary vascular resistance; RV = right ventricular; S' = systolic velocity of the tricuspid annulus; TAPSE = tricuspid annular plane systolic excursion; TR = tricuspid regurgitation.

Acute inflammatory cardiomyopathy notwithstanding (37-40), reverse remodeling only rarely translates into recovery of cardiac function sufficient to permit device explantation (41). Maybaum et al. (42) reported recovery in 9% of pulsatile LVAD recipients, while the HeartMate II investigators noted recovery in only 2.5% (43). Birks et al. (44) achieved long-term recovery in 8 of 20 continuous-flow LVAD recipients with nonischemic cardiomyopathy using a protocol involving the administration of a beta-agonist, but such promising results have yet to be validated by others.

Given that the majority of LVAD patients will remain dependent on DMCS in the long term, accurate noninvasive means of hemodynamic assessment are critical for monitoring and management. Until very recently, however, attempts to correlate noninvasive and invasive hemodynamic measurements in the LVAD population have been limited in both sample size and scope (36,45).

Estep et al. (46) made significant recent progress in addressing this deficit, performing simultaneous TTE and right heart catheterization in 50 patients supported by the HeartMate II (Table 4). Doppler assessment of right-sided pressures generally correlated well with invasive measurements. Echocardiographic measures of left-sided filling pressures were more problematic, however. Confirming earlier findings by Topilsky et al. (45), an estimate of left atrial pressure derived from right atrial pressure and position of the interatrial septum correlated modestly with pulmonary capillary wedge pressure (PCWP) but could be adequately obtained in only about two-thirds of patients. The E/e’ ratio neither correlated significantly with mean PCWP nor differed between patients with and without elevated PCWP. An

function may also improve during LVAD support (25,26), although results have been mixed (9).

The chief limitation of serial study during LVAD support is the inability to distinguish between the effects of mechanical unloading and changes at the level of the myocardium. Because continuous-flow devices lack valves, pump discontinuation results in regurgitant flow, limiting the accurate assessment of native cardiac function. So-called turn-down studies have attempted to circumvent this problem, reducing pump speed to the point at which forward and regurgitant LVAD flows are thought to be in equilibrium (32). Such studies have noted that ventricular function improves after LVAD placement (33,34) and persists at 1 year (34). Stress echocardiography has also been used to assess for myocardial recovery in the pulsatile era (35) and is feasible in continuous-flow devices (36).

FIGURE 1  Cardiac Tamponade Due to Post-LVAD Hemopericardium

(A) The parasternal long-axis view (Online Video 1) demonstrates normal geometry of the left and right ventricles post-left ventricular assist device (LVAD) implantation, with a trivial pericardial effusion. (B) The same patient and view 6 h later (Online Video 2) demonstrates a collapsed left ventricle, invaginated right ventricle, and large circumferential pericardial effusion. The inlet cannula is visible in both images as a linear structure within the left ventricular cavity. Note that the scale differs between A and B.
algorithm on the basis of mitral inflow velocities, right atrial pressure, and left atrial volume index demonstrated 90% predictive accuracy in distinguishing patients with and without elevated PCWP and was feasible in three-quarters of patients.

As an accompanying editorial underscored, these important findings await validation with other continuous-flow devices, such as the centrifugal-flow HeartWare HVAD (47). Given that axial- and centrifugal-flow devices have different flow dynamics (48), it cannot be assumed that noninvasive hemodynamic measurements are comparable across all continuous-flow devices. Furthermore, newer-generation devices are implanted in the pericardial space, making them especially prone to “waterfall artifact” originating near the LV apex, limiting Doppler examination of the mitral valve (Figure 2, Online Video 3) and the left atrium (49,50). Mitral inflow E velocity is a candidate echocardiographic surrogate of LV filling pressures (Figure 3), but off-axis views are required (5,50). Evaluating RV size and function is also challenging among patients supported by the HeartWare HVAD because of acoustic artifacts, obligating off-axis, foreshortened apical views (Figure 4).

DIAGNOSIS OF COMPLICATIONS

GENERAL APPROACH. LVAD alarms, abnormal device parameters, or clinical symptoms of heart failure should prompt evaluation with TTE. The echocardiogram may demonstrate rightward deviation of the interventricular septum, worsened functional MR, and/or more frequent aortic valve opening, indicating primary device malfunction, inflow or outflow obstruction, or pump thrombosis (51). High-velocity, turbulent flow may be seen in outflow obstruction, but this is not a well-validated finding (5). A state of elevated systemic vascular resistance may also present with low flow and high power, but TTE may show a unique combination of a closed aortic valve and high-velocity, pulsatile forward flow in the outflow cannula. Low pump flow with low power suggests either intermittent cannula obstruction or a state of low LV preload, as may occur with hypovolemia, severe TR, RV dysfunction (Figure 4), ventricular tachycardia, or cardiac tamponade (Figure 1, Online Videos 1 and 2). Persistently high pump flow in the setting of a low systemic cardiac output state raises concern for de novo severe AI (24).

PUMP THROMBOSIS. Pump thrombosis is a major cause of morbidity and mortality in DMCS, frequently necessitating pump exchange (52). Serum markers of hemolysis such as lactate dehydrogenase raise suspicion for thrombosis but are not confirmatory, and the clinical presentation may be indistinguishable from other causes of circulatory dysfunction. There may be an increase in power consumption (often presenting as high-power “spikes”), and TTE may demonstrate a dilated left ventricle, severe MR, and aortic valve opening on every beat, suggesting a failure of appropriate mechanical LV unloading (51).

However, pump and echocardiographic parameters may not necessarily change in the presence of early low-grade, nonocclusive thrombus (53). Computed tomographic angiography is useful for evaluating cannula position, patency of the outflow graft, and integrity of the bend relief (the rigid tube stabilizing the proximal outflow graft) (54) but cannot directly visualize the pump interior (49).

Uriel et al. (55) performed echocardiographic speed ramp studies in 17 HeartMate II patients with suspected thrombosis, finding that patients with confirmed thrombosis or obstructed bend relief demonstrated an attenuation of the expected relationship of LV decompression (as measured by left ventricular end-diastolic diameter [LVEDD]) with progressively increased pump speed. Patients with thrombosis also showed less change in pulsatility

| TABLE 4 Validation of Noninvasive Hemodynamic Measurements in the HeartMate II |

<table>
<thead>
<tr>
<th>Echocardiographic Parameter</th>
<th>Invasive Parameter</th>
<th>Patients With Adequate Image, $r$</th>
<th>$p$ Value</th>
<th>Ref. #</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP, mm Hg*</td>
<td>RAP</td>
<td>25 (81)</td>
<td>0.863</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>sPAP, mm Hg</td>
<td>sPAP</td>
<td>23 (74)</td>
<td>0.880</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>PVR, WU†</td>
<td>PVR</td>
<td>27 (67.5)</td>
<td>0.643</td>
<td>0.001</td>
</tr>
<tr>
<td>RVOT SV, cm</td>
<td>RVOT</td>
<td>5 SV</td>
<td>0.660</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

*RAP was estimated via inferior vena cava diameter and variation with respiration. †Echocardiographic PVR in Wood units (WU) was calculated as the ratio of peak tricuspid regurgitation velocity (m/s) to the right ventricular outflow tract time-velocity integral (cm) × 0.16. Invasive PVR was calculated as transpulmonary gradient (mm Hg) divided by cardiac output (thermodilution method; l/min). ILAP was estimated as RAP = 5 (for diastolic intraventricular septal position to the right), RAP = 5 (for diastolic intraventricular septal position to the left), or equal to RAP (for midline diastolic intraventricular septal position). \( \text{ILAV} \) was calculated using the biplane method of disks indexed to body surface area. A = mitral inflow late diastolic filling velocity; CO = cardiac output; dPAP = diastolic pulmonary artery pressure; DT = mitral inflow deceleration time; E = mitral inflow early diastolic peak filling velocity; \( \text{e}^' \) = average early diastolic mitral annular velocity; LAP = estimated left atrial pressure; LAVi = left atrial volume index; LVEDD = left ventricular end-diastolic dimension; NR = not reported; PCWP = pulmonary capillary wedge pressure; PVR = pulmonary vascular resistance; RAP = mean right atrial pressure; RVOT = right-ventricular outflow tract; \( S^' \) = peak systolic mitral annular velocity; sPAP = systolic pulmonary artery pressure; SV = stroke volume.

The table shows a comparison of invasive and noninvasive measurements for hemodynamic parameters in the HeartMate II LVAD system. The correlation coefficients ($r$) and $p$ values indicate the strength and significance of the relationship between invasive and echocardiographic measurements, with values closer to 1 indicating a stronger correlation and $p$ values less than 0.05 indicating statistical significance.
index and greater change in power consumption with increased speed, as well as a higher pump speed required for persistent aortic valve closure. Estep et al. (56) demonstrated that a simplified speed ramp test with fewer speed settings could accurately diagnose pump thrombosis.

Speed ramp diagnosis of pump thrombosis is not without limitations. Case reports suggest that speed

Because of apical-view artifact (Figure 2), off-axis views (as is demonstrated by this example) may be necessary for Doppler examination of the mitral valve.
ramp studies may show false-positive results in the setting of AI and false-negative results in the setting of inotropic and diuretic agents (57). In addition, physiologic differences between axial and centrifugal pumps (50) may limit generalizability. A ramp study for speed optimization performed in 15 HeartWare HVAD patients without suspicion for thrombosis showed no significant change in LVEDD with increased speed within the usual working range of the device (58).

There is evidence that device thrombosis may be diagnosed on TTE without ramp testing. Fine et al. (59) showed that decreased cannula diastolic flow velocity and increased systolic/diastolic flow velocity ratio correlated with device thrombosis in the HeartMate II. These parameters returned to their baseline values with intensified anticoagulation, suggesting potential utility for monitoring treatment response. A major limitation of the applicability of this technique beyond HeartMate II patients is acoustic artifact preventing adequate Doppler interrogation of the inflow cannula, particularly with intrapericardial pumps (Figure 2) (5,50).

### SPEED OPTIMIZATION

As a general principle, LVAD speed should be set high enough to provide adequate cardiac output and ventricular pressure unloading but low enough to avoid complete aortic valve closure and suction events (5,12,49). The position of the interventricular septum has been proposed as a tool to guide speed optimization, with rightward deviation suggesting inadequate support and leftward deviation implying excessive LV decompression, although such practices have not been validated with simultaneous invasive hemodynamic measurements (5,49). Exercise capacity varies with the degree of residual LV function, and exercise stress may have a role in speed optimization (60). Continuous-flow DMCS is an independent risk factor for AI, and the likelihood of de novo AI is increased with persistent valve closure (7,61).

Uriel et al. (55) demonstrated that pump optimization via protocolized speed ramp study is feasible and safe. Twenty-eight HeartMate II patients underwent an optimization study in which pump speed was increased incrementally, with serial monitoring of pump parameters, limited echocardiographic parameters, and Doppler-obtained blood pressure. Speed was set to maintain a mean arterial pressure > 65 mm Hg, midline interventricular septal position, and intermittent aortic valve opening, with no more than minimal MR. Testing was stopped if suction events occurred or LVEDD decreased to <3.0 cm.

Twenty-two suction events occurred, none with sustained ventricular arrhythmias, and there were no adverse events. Pump speed was changed in 17 patients (61%) as a result of testing.

Such an approach to pump optimization is intuitive and supported by some evidence, with leftward interventricular septal deviation at 30 days post-implantation associated with adverse outcomes, including recurrent heart failure and mortality (45). Unfortunately, LVEDD has recently been shown to have no correlation with mean PCWP in HeartMate II patients (46), calling into question its utility as a marker to guide decompression of the left ventricle.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HeartMate II (n = 28)</th>
<th>HeartWare HVAD (n = 15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope of LVEDD</td>
<td>−0.29 ± 0.11*</td>
<td>−0.0004 ± 0.0003</td>
</tr>
<tr>
<td>Speed of complete aortic valve closure, rpm</td>
<td>9,124 ± 1,222</td>
<td>2,881 ± 229</td>
</tr>
<tr>
<td>Degree of MR at final speed post-ramp test</td>
<td>None or mild</td>
<td>Variable</td>
</tr>
<tr>
<td>Suction events</td>
<td>22 of 52 total tests (42%)</td>
<td>1 of 18 total tests (5.6%)</td>
</tr>
<tr>
<td>Reference</td>
<td>55</td>
<td>58</td>
</tr>
</tbody>
</table>

Values are mean ± SD or n (%). *Statistically significant compared with LVEDD slope in HeartMate II patients with confirmed device thrombosis, −0.08 ± 0.04 (p < 0.001).

LVEDD = left ventricular end-diastolic dimension; MR = mitral regurgitation.
Furthermore, among the HeartWare HVAD patients included in a similar speed ramp protocol, LVEDD decreased minimally with increased pump speed (Table 5); such evidence should serve to discourage the routine targeting of reduced LVEDD for all continuous-flow DMCS devices as a method for “mechanically unloading” the left ventricle (58). Given important physiologic differences between axial-flow and centrifugal continuous-flow devices (48), additional research is necessary to develop device-specific ramp protocols, to investigate the correlation with invasive hemodynamic markers, and to assess the impact of speed optimization on outcomes.

CONCLUSIONS

We anticipate that echocardiography will remain the imaging modality of choice for pre-operative risk stratification, perioperative assessment, hemodynamic optimization, troubleshooting of complications, and longitudinal monitoring in the rapidly growing DMCS population. On the basis of our review of the evidence, we recommend the following as next steps for advancing the use of echocardiography in DMCS:

- Multicenter, prospective investigation of echocardiographic predictors of post-LVAD RV failure
- Investigation of TEE-guided initial device settings on the immediate post-operative course
- Validation of noninvasive hemodynamic measurements in centrifugal-flow devices
- Development of a protocol for the off-axis imaging of mitral inflow velocities in intrapericardial devices
- Validation of speed ramp studies for the diagnosis of device thrombosis in centrifugal-flow devices
- A randomized clinical trial of speed optimization by echocardiographic speed ramp study versus invasive hemodynamic measurements
- Development of evidence-based guidelines by an expert body

Finally, as the focus of investigation in DMCS shifts from survival to maximizing health-related quality of life and functional capacity (62), echocardiography has the potential to provide objective correlates for symptoms. Once the evidence base for echocardiography in DMCS has been more rigorously established, subsequent research should attempt to connect physiology with patient-tailored care.

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APPENDIX For accompanying videos, please see the online version of this article.