Use of Echocardiography to Optimize Left Ventricular Assist Devices

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Abstract

The burgeoning ranks of patients with heart failure, the limited number of organs available for heart transplant, and technological improvements have made ventricular assist devices (VADs) important therapeutic options for patients with acute cardiac decompensation and chronic end-stage heart failure. The increased use of VADs has been paralleled by an increased use of transthoracic and transesophageal echocardiography in patients who are candidates for long-term mechanical circulatory support. In particular, echocardiography is becoming an important part of tailoring VADs to specific patient needs. This review discusses current echocardiographic assessments used in the optimization of VAD settings and suggests novel methods that may become part of standard echocardiographic VAD optimization in the future.

Keywords

Ventricular assist device, echocardiography, optimization

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There are at least five million patients with heart failure (HF) in the US, 5% of whom are considered end-stage. 1 Mechanical circulatory support (MCS) in the form of ventricular assist devices (VADs) is becoming an increasingly important option for these patients. Previously reserved for rescuing patients in the throes of refractory cardiogenic shock, MCS is now a mainstay of end-stage heart failure treatment as a bridge to transplant, a bridge to recovery, and a destination therapy (DT). In some cases, MCS is used to bridge patients to decision, giving the patient more time to undergo transplant candidacy work-up. Recent improvements in technology have reduced the size of VADs and made them safer and more durable. Newer VADs also provide greater flexibility in tuning the settings to the particular and changing hemodynamic support requirements of individual patients. While a number of patient factors and device measures provide clues to the optimization of VADs, echocardiography has emerged as an important guide to tailoring VAD settings.

A detailed discussion of the history, uses, and types of MCS is beyond the scope of this article. In brief, MCS has traditionally been implanted in patients suffering from what was presumed to be reversible, acute cardiogenic shock refractory to other measures (bridge to recovery), 2 and in patients with New York Heart Association (NYHA) class IV HF to stabilize them prior to transplant (bridge to transplant). 3 A recent report from a registry spanning a 10-year period found that 16.5% of 11,336 transplant recipients were supported by VADs prior to transplant, and a more recent update from the United Network for Organ Sharing (2005) reported that 29% of patients are supported with left ventricular assist devices (LVADs) at the time of transplant. 4 VADs have demonstrated improvements in the function of many vital organs. Whether pre-transplant use of VADs improves post-transplant survival is controversial. 5,4

Despite increasing recognition of the need for organs, only about 2,500 hearts are available for transplant in the US each year, and this number has not changed significantly in recent years. Active research for many decades has produced great strides in the development of the total artificial heart, but technical setbacks translating into important limitations continue to complicate its clinical application. A major development came in 2001 with the publication of the Randomized Evaluation of Mechanical Assistance for the Treatment of Congestive Heart Failure (REMATCH) trial, which established the clear superiority of permanent LVADs over standard HF therapy in a population of patients with end-stage HF who were not candidates for orthotopic heart transplantation. 6 Admittedly, the two-year survival advantage was 23 versus 8%, and LVAD patients suffered more infections and strokes; however, there was also a clear advantage in symptoms and quality of life scores. In the subsequent nine years, the use of LVADs as DT has increased substantially. Improved patient selection has been shown to improve two-year survival to over 40%. 7

More recently, the results of the HeartMate II Destination Therapy Trial have shown that with a combination of a more durable LVAD (the non-pulsatile axial flow pump HeartMate II) and improved patient selection, the two-year survival rate can be improved to 60%. 8 This improvement and
clear superiority over the HeartMate I led to the recent US Food and Drug Administration (FDA) approval of the HeartMate II for DT of end-stage HF. Since the number of patients implanted with LVADs for DT will inevitably increase, the need for incisive clinical tools, including echocardiography, to guide patient selection and optimization of cardiovascular function post-LVAD implantation is becoming increasingly important.

Candidacy for DT with an LVAD includes:

- refractory NYHA class IV HF symptoms while on maximal medical therapy, including need for continuous inotropic support;
- left ventricular ejection fraction (LVEF) <25–30%; and
- peak maximal oxygen consumption <12ml/kg/minute.

Patients usually have an estimated one-year mortality of >50% and/or life expectancy of under two years. Additional hemodynamic cut-offs considered to support the diagnosis of refractory HF include cardiac index <2l/minute/m², pulmonary capillary wedge pressure >20mmHg, and systolic blood pressure <80mmHg.

Echocardiography and Ventricular Assist Devices

Echocardiography plays an important role in the management of patients being considered for or currently supported on an LVAD. Before implantation, echocardiography establishes LVEF, an important criterion for VAD candidacy, and assists in the risk stratification of severe right ventricular (RV) failure requiring RV mechanical support. An extremely important consideration is that one-time assessment of RV function in patients with chronic congestive heart failure can be very misleading. There is a tight coupling of RV systolic performance to the pulmonary afterload, and considerable plasticity of the RV has been observed in response to hemodynamic changes. Indeed, re-imaging after a successful ‘tune-up’ or optimization of a severely congested HF patient can result in a marked improvement of RV systolic function—proof that the dynamic range in load-sensitive RV can be very significant in individual patients.

Echocardiography also identifies important clinical factors that complicate VAD placement, including intracardiac thrombi, aortic regurgitation, severe tricuspid regurgitation, atrial and ventricular septal defects, and ascending aortic dissection or severe atherosclerosis. Intraoperative transesophageal echocardiography guides the placement of inflow LVAD cannulae in the LV apex or left atrium and of the outflow cannula in the ascending aorta. After implantation, echocardiography aids in the diagnosis of VAD dysfunction, including identification of thrombosis, obstruction or kinking of the inflow and outflow cannulae, RV dysfunction, pericardial tamponade, VAD-associated endocarditis, aortic insufficiency, and VAD regurgitation.

Optimization of Left Ventricular Assist Device Settings

Different types of VAD have different pumping mechanisms. The two main mechanisms involve pulsatile and continuous flow. Pulsatile VADs can be set at either a fixed or an automatic mode. Fixed-rate settings pump blood at a set heart rate, irrespective of the amount of blood volume in the chamber, while automatic modes vary the rate to pump a constant amount of blood with each beat. A rarely used third mode involves gating the timing of pumping to the electrocardiogram (EKG). VAD settings can be changed by adjusting either the pumping rate or the amount of blood pumped, depending on the mode.

Continuous-flow VADs use either axial or centrifugal flow mechanisms that employ a rotating propeller or a rotating plate, respectively. The rotor speed and the pressure differential between the inflow and outflow chambers determine the rate of continuous flow. Continuous-flow VADs do not actually produce completely non-pulsatile blood flow. Residual ventricular function and non-uniform pressure differences generate some degree of pulsatility, measured by the pulsatility index (PI) in the HeartMate II. PI increases with ventricular filling and decreases with ventricular unloading. Continuous flow VADs can be adjusted by changing the speed of the rotor, measured in revolutions per minute (rpm).

In general, optimizing VAD flows involves finding a (sometimes delicate) balance between ventricular volume overload and underfilling. Increasing VAD rpm will decompress the ventricle and, in some cases, lead to reverse remodeling and ventricular recovery. On the other hand, excessive unloading of a ventricle can cause myocardial atrophy, mask ventricular recovery, and worsen states such as dehydration, sepsis, anemia, and pericardial tamponade with phenomena known as ‘suck-down’ events. Here, myocardial structures such as trabeculations, papillary muscles, chordal structures, and aneurysmal wall segments can be drawn into the inflow cannula, resulting in transient obstruction.

VAD optimization by echocardiography essentially involves making echocardiographic assessments and measurements during adjustments of pumping rates, output volume, or rotor speed. The simplest echocardiographic assessment of LV filling is neutral alignment of the interventricular septum. In cases of volume overload, the septum will bow into the RV. If the ventricle is underfilled or, in the case of a continuous-flow device, there is excessive unloading with the rpm set too high, the septum will bow into the LV. A neutrally oriented septum suggests the preferable state of mechanical unloading. In cases of insufficient unloading of the ventricle, the rotor speed or pumping rate...
or volume can be increased until the septum no longer bows into the RV and the LV has decreased in size. If the ventricle is underfilled and/or trabeculations or other ventricular structures impede inflow, the rotor speed or pump rate/volume can be decreased (see Figure 1).

Optimizing VAD filling by assessment of septal neutrality has several pitfalls. First, septal bowing may be caused by factors other than abnormal ventricular filling. Elevated RV pressures from RV outlet obstruction, acute pulmonary embolism, or the many subcategories of pulmonary arterial and pulmonary venous hypertension can cause septal flattening. Conduction delays/bundle branch blocks, pericardial tamponade and constriction, and post-sternotomy state often cause a septal paradox that can mimic flattening. LVAD inflow or outflow cannula obstruction from thrombus, malposition, or kink can lead to distension of the LV, even in the underfilled state. A complete echocardiographic examination is necessary to exclude other causes of septal shift. Perhaps most importantly, ventricular septal neutrality is a non-quantitative, qualitative assessment that may be subject to significant inter- and intra-interpreter variability.

Chamber size presents another echocardiographic measure of ventricular loading in patients with LVADs. 3D assessments of LV volumes are the most accurate echocardiographic measures of chamber sizes and have proved to be reproducible. However, even realtime 3D echocardiographic measurements require some degree of offline analysis, and some LVAD patients lack high-quality imaging windows necessary for accurate 3D endocardial tracing (especially at the apical site of cannula insertion). An easier method available even in patients with difficult imaging windows is LV end diastolic diameter (LVEDD), measured in the parasternal long-axis view at the mitral valve leaflet tips. LVEDD can be measured from either 2D or M-mode images and constitutes a quantitative and reproducible assessment of ventricular size. LVEDD does not necessarily reflect accurate volumes, particularly in remodeled ventricles with wall motion abnormalities (including septal paradox). Care must be taken to measure chamber dimensions in precisely the same imaging plane each time, and to measure along an axis perpendicular to the septal and inferolateral walls.

Another form of VAD optimization involves imaging the aortic valve. By mechanically unloading the ventricle, VADs prevent blood from being ejected through the aortic valve. Thus, the aortic valve may not open, or may open minimally and intermittently. The outflow cannula in the ascending aorta provides flow into the ascending aorta and into the aortic root. In pulsatile VADs, the high blood flow prevents thrombus formation. In non-pulsatile VADs, however, flow velocity is reduced and stasis in the aortic root can lead to thrombus formation at the aortic valve or sinus of Valsalva, leading to stroke. Anticoagulation can prevent this potentially catastrophic complication, but the rotor speed can also be adjusted to allow some forward flow through the aortic valve. M-mode and 2D imaging can demonstrate the degree and frequency of aortic valve opening (see Figure 2).

Echocardiography also plays a crucial role in assessing ventricular recovery, particularly during LVAD ‘pump-off’ or ‘turn-down’ testing. As VAD support is gradually decreased during testing of myocardial function with minimal mechanical support, the LVEDD will increase in response to increased afterload and preload. The degree to which this change is minimal and accompanied by an increase in LVEF after 15 minutes is suggestive of myocardial recovery. In small studies, LVEF >45% and LVEDD <5.5cm at the time the LVAD was turned down to minimal mechanical support predicted ventricular recovery. In a separate study, inferolateral basal wall motion recovery portended successful VAD weaning in patients with acute myocarditis. Dobutamine stress testing has been advocated to measure LV reserve in the form of improved LVEF, and thereby to predict recovery. More simply, an increase in degree and frequency of aortic valve opening on full mechanical circulatory support is a sign of improved ventricular function and suggests that VAD weaning may be possible.

**Figure 2: M-mode of the Aortic Valve in Left Ventricular Assist Device Patients**

M-mode recordings through the aortic valve in the parasternal long-axis view show a straight line (arrow) at the leaflets in panel A, indicating no opening of the valve over three cardiac cycles. In panel B, there is opening in systole (arrow) with every beat.

**Novel Echo Techniques for Ventricular Assist Device Optimization**

Predicting ventricular recovery and optimizing VAD settings may involve detecting subtle alterations in ventricular performance in response to changes in VAD settings. Myocardial strain is a measure of change in length relative to initial length. It is relatively less dependent on filling pressures than chamber dimensions, volumes, and ejection fraction,
and therefore represents a better assessment of intrinsic myocardial contractility. Changes in strain over time may provide a sensitive marker to predict ventricular recovery, but strain imaging may also allow fine-tuning of VAD settings to optimize myocardial performance. Myocardial strain can be measured in different tissue segments but also averaged to provide global strain.

Strain is commonly measured by two different echocardiographic techniques. Tissue Doppler imaging (TDI) measures tissue velocity (see Figure 3). Tissue velocity can be used to calculate strain rate, which can be integrated over time to yield strain. TDI has a major drawback in that, as a Doppler modality, it is dependent on the angle of orientation of the ultrasound beam relative to the direction of tissue movement. If the Doppler ultrasound beam and vector of tissue movement are not parallel, tissue velocity will be underestimated. A different modality, speckle tracking (ST), mostly overcomes this problem by measuring the movement of ultrasound speckles (artifacts created by inhomogeneous ultrasound backscatter) in the myocardium. Using 2D images, ST can measure distance of speckle movement in any direction within the 2D plane. From this distance, ST algorithms compute velocity, strain, and strain rate. In order to accurately track the speckles, high frame rates are required, but this is not always possible to achieve. Furthermore, speckles move outside the 2D imaging plane. ST algorithms attempt to compensate with mathematical modeling, but through-plane motion remains a significant limitation. 3D ST is available but currently limited by sub-optimal frame rates in many patients.

LVADs have differing effects on the RV. They can reduce RV afterload by reducing LV preload and pulmonary pressure, but they can increase RV preload by increasing the trans-systemic circulating blood volume. RVs with marginal reserve may fail in the face of increasing preload with VAD insertion, or may fail during VAD weaning when pulmonary pressures increase. Specifically, the RV may increase in size over time due to increased preload, and if the decrease in pulmonary afterload is not matched by an increase in cardiac output, there will be a decrease in RV stroke work. An isolated echocardiographic measure of RV size and function, especially in the absence of symptoms, may not be indicative of clinically significant RV failure.

Pulmonary vascular resistance (PVR) may be an important measurement and target for interventions (pulmonary arteriolar vasodilators) in patients undergoing LVAD weaning. Non-invasive measurement of PVR by echocardiography may use the formula:

$$PVR = \left( \frac{V_{\text{maxTR}}}{VTI_{RVOT}} \right)_{10} + 0.16$$

where $PVR = \text{pulmonary vascular resistance in Wood units}$, $V_{\text{maxTR}} = \text{maximal tricuspid regurgitation velocity}$, and $VTI_{RVOT} = \text{velocity time integral of the RV outflow tract}$. Echocardiographic PVR was reduced at six months post-implant and predicted improvements in six-minute walking distance (6MWD) and Minnesota Living With Heart Failure Questionnaire in a small study of end-stage HF patients with non-pulsatile LVADs.

**Conclusion**

LVADs have become an important part of the care of end-stage HF patients. Echocardiographically guided optimization may improve LVAD performance and identify patients with ventricular recovery. Traditional assessments of septal neutrality, chamber sizes, and aortic valve opening may be augmented in the future by tissue Doppler and ST measures of myocardial performance and non-invasive measures of pulmonary vascular resistance.
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