Echocardiography in the Management of Patients with Left Ventricular Assist Devices

Rebecca T. Hahn, MD
Associate Professor of Medicine
Director of Interventional Echocardiography
Columbia University

This document addresses the role of echocardiography during the different phases of care of patients with FDA-approved long-term, surgically implanted LVADs.

The phases of patient care addressed include preoperative patient selection, perioperative TEE imaging, postoperative surveillance, optimization of LVAD function, problem-focused exams (when the patient has signs or symptoms of LVAD or native cardiac dysfunction), and evaluation of native myocardial recovery.

Suggested protocols, checklists, and worksheets for each of these phases of care are located in the Appendices. Other types of MCS may also be encountered by echocardiographers, and these devices are discussed in Appendix A.

Although echocardiography is frequently used for managing LVAD therapy, published data intended to guide timing and necessary data collection remain limited. Some of the recommendations provided herein are based on expert consensus from high-volume MCS implant centers.

Most LVAD recipients are adults with dilated cardiomyopathies. Other LVAD patient populations addressed within this document include those with smaller hearts (e.g., resulting from restrictive cardiomyopathies) and those with pediatric and congenital heart disease.


Ventricular Assist Devices

- LV Assist Devices used in end-stage heart failure as:
  - Bridge to heart transplant
  - Destination therapy
    - REMATCH (Randomized Evaluation of Mechanical Assistance for the Treatment of Congestive Heart Failure), trial: 129 patients ineligible for OHT randomized to LVAD or medical therapy

Rose EA et al. N Engl J Med 2001;345(20);1435-1443

LVAD Components

- Inflow cannula to drain blood from the left ventricle or left atrium
- Mechanical impella (pump) to propel blood
- Outflow cannula to return the blood to the aorta.
- Percutaneous drive line (control and power wires)
- Connects to external portable drive and power supply

Terminology of Pumps

- Pulsatile versus Continuous
  - Pulsatile uses a positive displacement pump
  - Continuous uses either
    - Axial Flow Pump
    - Centrifugal Flow Pump
Comparison of LVAD Types

**Pulsatile-Flow**
- Internal chamber, inflow/outflow valves for cyclic flow, pneumatic or electric driven diaphragm
- Large diameter percutaneous leads
- Loud functioning sound of the device
- Large surgical incision
- High friction in pump
- High morbidity (hemolysis)

**Continuous-Flow**
- Nonpulsatile flow with no valves, small cannulas, magnetically coupled motor (direct-drive, self-bearing or bearingless) or axial rotor
- Better durability (simpler mechanics) and quieter
- Increased blood flow (to 1 L/min) reduced blood stasis and hemolysis

Difference in flow patterns
- **Pulsatile devices:**
  - Peak flows are higher in the pulsatile than in the axial propulsion device because the pump stroke volume occurs only during device systole
  - The pulsatile device depends exclusively on filling of its chamber for ejection and does not keep any fixed relationship with the electrocardiogram.
- **Continuous Flow Devices**
  - Lower peak flows but throughout cardiac cycle
  - Pulsatility correlates with cardiac cycle
    - Changes in pressure gradient across the device produced by ventricular contraction.

Types of Ventricular Assist Devices

- **Pulseatile Flow Pumps**
  - Thoratec HeartMate® Extended Lead Vented Electric (XVE).
  - Novacor® Left Ventricular Assist System (LVAS)
  - Thoratec VAD system (biventricular support)

- **Continuous Flow Pumps**
  - Thoratec HeartMate II ®
  - HeartWare HVAD Ventricular Assist System
  - Tandem Heart®
  - Impella® Devices

The Thoratec HeartMate® II LVAD

- Continuous Flow Pump
  - The Thoratec HeartMate II LVAS (Left Ventricular Assist Device)
    - Employs a rotary blood pump that is expected to have a significantly greater pump-life than the mechanism used in the HeartMate VE and XVE.
    - Is about 1/8th the size of the HeartMate XVE and is therefore suitable for a wider range of patients, including petite adults and children.
    - Automatic speed control mode that is designed to regulate pumping activity based on different levels of patient or cardiac activity.
    - The HM-II impeller and its housing structure are implanted below the diaphragm.

HeartWare HVAD Ventricular Assist System

- HVAD impeller and its housing structure are implanted above the diaphragm, within the pericardial sac.
Pre-operative Echo Assessment

### Table 1 Preimplantation TTE/TEE “red flag” findings

<table>
<thead>
<tr>
<th>Location</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Left Ventricle and Interventricular Septum</strong></td>
<td>Small LV size, particularly with increased LV trabeculation</td>
</tr>
<tr>
<td></td>
<td>LV thrombus</td>
</tr>
<tr>
<td></td>
<td>LV apical aneurysm</td>
</tr>
<tr>
<td><strong>Right Ventricle</strong></td>
<td>RV dilatation</td>
</tr>
<tr>
<td></td>
<td>RV systolic dysfunction</td>
</tr>
<tr>
<td><strong>Atria, Interventricular Septum, and Inferior Vena Cava</strong></td>
<td>Left atrial appendage thrombus</td>
</tr>
<tr>
<td><strong>Valvular Abnormalities</strong></td>
<td>Any prosthesis valve (especially mechanical AV or MV)</td>
</tr>
<tr>
<td></td>
<td>&gt; mild AR</td>
</tr>
<tr>
<td></td>
<td>&gt; moderate MS (Note: any MR is acceptable)</td>
</tr>
<tr>
<td></td>
<td>&gt; moderate TR or &gt; mild TS</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td>Any congenital heart disease</td>
</tr>
<tr>
<td></td>
<td>Aortic pathology: aneurysm, dissection, atheroma, occlusion</td>
</tr>
<tr>
<td></td>
<td>Mobile mass lesion</td>
</tr>
<tr>
<td></td>
<td>Other shunts: patent ductus arteriosus, intrapulmonary</td>
</tr>
</tbody>
</table>


---

TTE Protocol

- Abnormalities of Importance:
  - Patent foramen ovale:
    - LV and LA pressure fall with LVAD
    - If LA pressure falls BELOW that of RA significant shunting occurs.
    - Prevalence ~ 9%
  - Aortic Regurgitation
    - Because LV pressures are low but aortic pressures are maintained, the retrograde gradient between the aorta and LV are very high.
    - AR (≥ 2+) may increase to significant AR post LVAD
    - AR increases LVAD preload and result in pump rate/flow upregulation
  - Mitrail Stenosis
    - May limit LV filling

- Right ventricular function
  - LVAD function depends on normal LV and LA filling pressures, thus on RV function.
  - RV fractional area change (FAC) < 20% are at higher risk of RV failure post LVAD
- Tricuspid Regurgitation
  - TR (≥ 2+) affects the accuracy of thermodilution cardiac output.
  - Because PAP falls post LVAD, TR frequently improves
- Left ventricular Apex Anatomy
  - Wall thickness (may determine cannula size)
  - Apical thrombus
  - Aortic atheroma or aneurysm
  - TEE assessment of cannulation site

Scala GM et al. JASE 2000;13:754-63

---

Pre-operative Echo Assessment

- Intracavitary Thrombus
  - Particularly in the LV apex
  - Aortic Atheroma and Aneurysm
    - TEE assessment of cannulation site

3D Aortic Atheroma
LV Apical Thrombus

Scala GM et al. JASE 2000;13:754-63
Valvular Heart Disease

- ≥ moderate TR, especially if associated with RV dysfunction, is as relative contraindication for LVAD
- Severe AS may be well-tolerated
- Mitral regurgitation is well-tolerated
- Mechanical AVR
  - Replace with bioprosthetic valve prior to LVAD
- Mechanical MVR
  - Normal function or MR of any severity may be left alone
  - Significant mechanical MV stenosis should replace with bioprostheses


Echo Parameters and LVAD Outcomes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>Tx</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVEF</td>
<td>&lt;25%</td>
<td>Qualifies for Destination Therapy</td>
</tr>
<tr>
<td>LVIDd</td>
<td>&lt;63 mm</td>
<td>Higher 30d morbidity/mortality post-LVAD</td>
</tr>
<tr>
<td>RV Fx</td>
<td>Peak Long Strain &lt;9.6%</td>
<td>Predictive of RV Failure post-LVAD</td>
</tr>
<tr>
<td>RV:LV end-diastolic diameter ratio of &gt;0.75</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Preimplantation TEE

- Reevaluation of the degree of AR
- Determination of the presence or absence of a cardiac-level shunt
- Identification of intracardiac thrombi
- Assessment of RV function, and evaluation of the degree of TR
- Determination of the degree of MS, PR, prosthetic dysfunction, possible vegetations, aortic disease, etc.

Diagnosing Patent Foramen Ovale

- Thorough color Doppler scanning of the fossa ovalis margins at a low Nyquist-limit setting and IV injection of agitated saline
- IV injection of agitated saline combined with a "ventilator" Valsalva maneuver (briefly sustained application of up to 30 cmH2O of intrathoracic pressure and, on opacification of the right atrium, release of the intrathoracic pressure.
- Injection of agitated saline into a femoral vein to avoid significant competitive inferior vena cava "negative contrast" flow in the fossa ovalis region

Intra-Procedural Echo Assessment
**Post-LVAD Intra-procedural Assessment**
- Monitor for intra-cardiac air
- Rule out shunt (sometimes difficult to assess prior to LVAD)
- Closed AV with no AR
- Assess TR (may be a sign of RV failure and need for RV support)
- Confirm device position and function:
  - Inflow cannula position correctly oriented toward the mitral valve with abutting LV wall
  - Exclude interference with sub-mitral apparatus
  - Spectral Doppler normal
  - Outflow cannula path adjacent to RV/RA
  - Anomalous to aorta not kinked with flow <2 m/s
- Confirm native heart function:
  - Neutral septum desirable
  - Small LV with right-to-left septal shift suggests over-pumping or RV failure
  - Large LV suggest obstruction or inadequate pump function

**Intra-procedural Assessment (Continuous Flow)**
- Good LVAD Function on Doppler
  - Inflow cannula
    - Unidirectional, continuous low velocity flow on color
    - Low velocity flow on PW with slight pulsatility
    - Velocities variable
    - With a pump flow of 5 L/min, velocities 60-120 cm/s
  - Outflow cannula
    - Low velocity flow on PW with slight pulsatility
    - Peak velocities 1-2 m/s


---

**Intra-procedural Echo Evaluation**
- Outflow and Inflow Cannulas:
  - LV apex/LA or LAA, ascending aorta, etc
  - Doppler
    - Flow pattern:
      - Continuous versus pulsatile
      - Uni- or bi-directional
      - Pari-cannular flow/leak
  - Aortic Valve
    - Is it opening? Should it open?
    - Aortic regurgitation
  - Relative ventricular volumes
    - LV size (and function)
    - Bowing of interventricular septum
  - Complications:
    - Pericardial effusion
    - Thrombus/vegetation
    - Valvular or Papillary muscle damage

**Post-Procedural Echo Assessment**

---

**Post-LVAD Follow-up**
- Note AV opening and AR
- Assess Inflow and Outflow cannula position and function
- Determine LVAD output
  - Area of cannula x VTI
- Determine total cardiac output
  - (RVOT SV)
- Exclude pericardial effusion/hematoma
- Assess septal shift
- Assess RV function

---

**Post-operative Echo Assessment**
- Note Pump Speed in addition to HR/BP
- Additional imaging
  - Inflow Cannula
  - Outflow Graft

**Post-operative Echo Assessment**

- **Right Heart Assessment**
  - Variable effects on RV size
    - May take months for RV remodeling to occur
    - Increased RV preload (from appropriate LV unloading) may increased TR and RV size
    - Reduction in PA pressures and PVR

- **Aortic Valve Assessment**
  - Valve opening during continuous LVAD support depends on the balance between
    - LV systolic function
    - LVAD pump speed
    - Degree of LV unloading
    - Loading conditions (pre- and after-load)

- **Indicators of LVAD Unloading of the LV**
  - Reduction in LVID of 20–30%
  - Reduction in LV volumes by 40–50%
  - Neutral or leftward shift of the septum
  - Reduction in MR secondary to LV remodeling

- **Aortic Valve Assessment**
  - AV Opening may occur
    - Sub-optimal LV unloading
  - Myocardial recovery

- **RVOT VTI increases**

**Systemic Cardiac Output Assessment**

RV CO represents the sum of LVAD and transaortic flow

Despite an increase in RV preload and possible increase in RV dimensions/volume, CO should increase in the setting of reduced PASP and PVR

**Pulmonary Pressure Assessment During LVAD Support**

Continuous LVAD:
- High pump speeds may be associated with increased TR, increased RVID and higher PASP in the setting of increased preload
- Evaluation of TR and septal shift during pump adjustment can be performed

**Mitral Valve Inflow Doppler Pattern at Various Continuous-Flow LVAD Pump Speed Settings**

Increasing pump speed is associated with reduction in mitral E and A velocities
Spectral Doppler Examination of LVAD Cannulas

<table>
<thead>
<tr>
<th>LVAD</th>
<th>Inflow Pk</th>
<th>Outflow Pk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsatile</td>
<td>&lt;2.5 m/s</td>
<td>~2.0 m/s</td>
</tr>
<tr>
<td>Continuous</td>
<td>&lt;2.0 m/s</td>
<td>&lt;1.5 m/s</td>
</tr>
</tbody>
</table>

LVAD Pulsatility Index: 
1's with "ing" LV contractility

Right Ventricular Hemodynamics
- Quantitative
  - Short-axis RVOT
  - Subpulmonary region
  - Pulmonic valve annulus
  - Main PA
  - Doppler
    - RVOT VTI
    - TR velocity

Calculating RV Stroke volume and Pulmonary Vascular Resistance important for follow-up

RV Stroke Volume = 33 cc
PVR = 3.3 WU

Post-operative LVAD Assessment
- Calculating Outflow Graft Stroke Volume

Calculating RV Stroke volume and Pulmonary Vascular Resistance important for follow-up

RAMP Study
- Assess LVIDd and position of the interventricular and interatrial septae
- Note AV opening (2D and M-mode) and AR
- Assess MR and TR
- Determine total cardiac output (RVOT SV)

Additional Echo Images for LVAD assessment
- Imaging of the inflow graft
  - LV apex (Heart Mate), LA (Tandem Heart) or LVOT (Impella)
  - Color and Pulsed Doppler of inflow graft
- Imaging of the outflow graft
  - Ascending aorta (Heart Mate), or ascending aorta just above AV (Impella)
  - Measure the diameter of the graft at the level of PW
  - Color and Pulsed Doppler of outflow graft

Low PI due to Trabecular Obstruction

Right Parasternal View
Post-operative LVAD Assessment: Mechanical Complications

- Differential diagnosis of low pump flow rates
  - Hypovolemia
  - Right ventricular failure
  - Severe TR
  - Inflow graft obstruction
  - Outflow graft obstruction
  - Tamponade
  - Pulmonary embolus


Post-operative LVAD Assessment

- Inflow Graft Obstruction
  - Interrupted flow in the intake cannula

Tamponade

- Echocardiographic pitfalls
  - Localized effusions (loculated)
  - Thrombus instead of fluid
  - Atrial tamponade (very little fluid/thrombus required)
  - Right ventricular tamponade from substernal thrombus
  - Standard Doppler assessment not accurate

Post-operative LVAD Assessment: Mechanical Complications

- Differential diagnosis of high pump flow rates
  - LV flow rate and RV output mismatch
  - Sepsis
  - LVAD volume overload
    - Qp/Qs < 1 (high LV compared to RV flow)
    - Aortic regurgitation
    - Inlet or outlet valve regurgitation
      - Diagnosed by PW Doppler
      - Note: flow is dissociated from ECG
    - Outlet graft (into aorta)
      - Use right parasternal view
      - Align flow (use PW)

Note variability of regurgitant jet flow profile depending on WHEN in the INTRINSIC cardiac cycle the regurgitation occurs
1. During LV systole
2. During LV diastole

Note: Pk Outflow velocity ≤ 1.8 m/s had Sn 84%, Sp 89% for Inflow Valve Regurgitation
Horton et al JACC 2005;45:1426-40
Post-operative LVAD Assessment

- Reversal of flow in Continuous LVAD pump failure
- Diastolic regurgitation through outflow graft from the aorta into the LV


Post-operative AV assessment

- Aortic valve
  - Thickness
    - Fusion of cusps has been described after prolonged LVAD therapy
  - Excursion
    - Describe AV opening:
      - Normal, partial, intermittent, complete AV closure
      - If LVAD fails, safety mode (fixed rate mode) may be initiated however some LV output is required and may be tested
      - When weaning the LVAD, AV excursion should be seen
  - Regurgitation

Echo Detection of Inflow Valve Regurgitation

Inflow Valve Regurgitation (IVR) is the most common cause of LVAD dysfunction


Thank you!
Transplant Techniques

Biastral Transplant
- Suboptimal hemodynamics:
  1. Abnormal LV filling pattern
  2. Predispose to atrial thrombus

Bicaval Transplant
- Improved hemodynamics:
  1. Abnormal LV filling pattern
  2. Lower risk of atrial thrombus


Normal appearance: Biastral Technique

Normal appearance: Bicaval Technique

Great Arteries

RV Size and Function
Acute Allograft Rejection and Cardiac Graft Vasculopathy

- Can echocardiography diagnose AAR and CAV?
  - Proposed parameters:
    - LV function:
      - M-mode FS
      - 2D EF

- Proposed parameters:
    - Sm ≤ 10 cm/s associated with a 97.2% likelihood for transplant CAD
    - Sm > 11 cm/s excludes CAD with 90.2% probability
    - E/E’ predicts CAD
      - E/E’ > 13 consistent with ↑PCWP
        - Estimated PCWP = 2.6 + 1.46(E/E’)
        - Sundereswaran L et al. Am J Cardiol 1998;83:352-357

- Nongeometric Myocardial Performance Index: The Tei Index

  - MPI = (IC + IRT)/ET
  - Normal adults
    - LV = 0.39 ± 0.04
    - RV = 0.28 ± 0.04
    - Unaffected by heart rate (range 50-120 bpm)
    - Unaffected by TR
    - In Ebstein Anomaly, RV MPI range 0.46 to 0.65
    - CC-TGA RV MPI 0.72 ± 0.17
      - Eidem, BW et al. JASE 1998;11:849-56
      - Eidem, BW et al. AJC 2000;86:654-8

Index of Myocardial Performance

- Increase in IMP may occur during AAR episodes and respond to therapy (Leonard JT et al. J Heart Lung Transplant 2006, 25:61-66.)
- Changes independent of baseline or change in EF
  - In Transplant Patients:
    - Mean right atrial pressure was related weakly to routine tricuspid inflow variables but strongly to tricuspid E/Em (r = 0.79; n = 38)
    - RAP = 1.76(E/Em) - 3.7

LV Mass

- Increase in wall thickness after HT
  - Repetitive rejection
  - Arterial hypertension
  - Immunosuppressive therapy
  - Chronic tachycardia
  - Denervation
- Progression related to cyclosporine levels and BP
- Predictive of 1 yr mortality
Cardiac Graft Vasculopathy

- CAV continues to be a significant cause of death after the first year of transplantation.
- The prevalence of CAV remains high: 20% at 3 years, 30% at 5 years, and 45% at 8 years after transplantation.
- Prevention of CAV
  - Optimize immunosuppression
  - Treat the comorbidities associated with CAV progression
- Diagnosis and monitoring
  - Coronary angiography
  - IVUS

Cardiac Graft Vasculopathy

- A normal DSE incorporating M-mode measurement of wall thickening predicts an uneventful clinical course, suggesting an excellent negative predictive value (justifies postponement of invasive studies).
- Changes between serial tests yielded important prognostic information. Serial normal DSE indicated a very low risk of events.
- The use of myocardial contrast echocardiography with dobutamine was moderately sensitive (70%) and very specific (96%) for the presence of 50% angiographic stenosis.

Tricuspid Regurgitation

- Natural history
  - Resolution within 1 month of HT (with normalization of PAP)
  - New onset due to injury during EMB: number of biopsies (≥31) predictive of TR

Tricuspid Regurgitation

- Prognosis of significant TR:
  - Symptomatic RV failure
  - Impaired renal function
  - Mortality
Pericardial Effusion

- Etiologies of large PE
  - Mismatch between recipient and donor hearts
  - AAR
  - Immunosuppressive drugs
  - Infection
- AAR diagnosis: Sn = 49%, Sp = 74%
- Typically benign and resolves spontaneously