Recommendations for Multimodality Imaging of Patients With Left Ventricular Assist Devices and Temporary Mechanical Support: Updated Recommendations from the American Society of Echocardiography

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INTRODUCTION

Advances over the past several years in temporary and durable left ventricular (LV) assist devices (LVADs) support the need for an updated perspective on the role of noninvasive imaging in contemporary mechanical circulatory support (MCS) management. These advances include the evolution and increased utilization of temporary MCS (TMCS) devices, adoption of the fully magnetically levitated durable HeartMate 3 (HM3; Abbott), and an increased availability and use of complementary multimodality imaging techniques, such as computed tomography (CT) and positron emission tomography (PET), to evaluate and manage complications associated with LVADs.[1,2]

This guideline will serve as an update to the 2015 comprehensive American Society of Echocardiography (ASE) LVAD guideline (hereinafter referred to as the "2015 Guideline") document that predominantly focused on long-term, surgically implanted continuous-flow LVADs.[3] The 2015 Guideline describes the preprocedural aspects of imaging and remains in effect. Since the publication of that guideline, the HeartMate II (HM-II) LVAD (Abbott; Supplemental Figure 1) and the HeartWare LVAD (HVAD; Medtronic; Supplemental Figure 2) are no longer being implanted, with the HVAD withdrawn from the market due to a high incidence of stroke and device malfunction[4]; however, there are many patients still being supported by these legacy devices. The basic principles and recommendations for the role of echocardiography in patient selection, preprocedural, intraprocedural, and postprocedural surveillance, and troubleshooting in patients with legacy LVADs remain in effect as outlined in the 2015 Guideline. This update will focus on the unique aspects of the HM3 LVAD, as well as provide more detailed information on TMCS devices. In addition, we will expand upon the role of multimodality imaging, including cardiac CT (CCT) and nuclear imaging in patients with LVADs.

This document, like the 2015 Guideline,[3] uses both published data and expert opinion from high-volume MCS implantation centers to provide consensus recommendations. In addition, our writing group includes experts from multiple disciplines including sonography, cardiology, cardiothoracic anesthesiology, cardiothoracic surgery, advanced heart failure (HF) and heart transplantation (HT), critical care, emergency medicine, interventional cardiology, and radiology. We have elected to carry over select key points from the previous document to provide a comprehensive summary for the use of echocardiography in the management of LVAD patients. Furthermore, we acknowledge the growing role of point-of-care ultrasound (POCUS), which may be useful in evaluating patients with MCS in selected clinical situations.

Abbreviations

2D = Two-dimensional

3D = Three-dimensional

ACHD = Adult congenital heart disease

AR = Aortic regurgitation

AS = Aortic stenosis

ASD = Atrial septal defect

ASE = American Society of Echocardiography

AV = Aortic valve

BP = Blood pressure

CCT = Cardiac computed tomography

CF = Continuous flow

CFD = Color-flow Doppler

CPB = Cardiopulmonary bypass

CS = Cardiogenic shock

CT = Computed tomography

CTA = Computed tomography angiography

CW = Continuous-wave

ECG = Electrocardiogram

ECMO = Extracorporeal membrane oxygenation

FDG = 18-F-fluorodeoxyglucose

HF = Heart failure

HM-II = HeartMate II left ventricular assist device

HM3 = HeartMate 3 left ventricular assist device

HT = Heart transplantation

HVAD = HeartWare left ventricular assist device

IABP = Intra-aortic balloon pump

IAS = Interatrial septum

IJ = Internal jugular

INTERMACS = Interagency Registry for Mechanically Assisted Circulatory Support

IVC = Inferior vena cava

IVS = Interventricular septum

LA = Left atrial/atrium

LAA = Left atrial appendage

LAP = Left atrial pressure

LV = Left ventricular/ventricle

LVAD = Left ventricular assist device

LVEF = Left ventricular ejection fraction

LVIDd = Left ventricular internal dimension at end diastole

LVOT = Left ventricular outflow tract

MCS = Mechanical circulatory support

MOMENTUM 3 = Multicenter Study of MagLev Technology in Patients Undergoing Mechanical Circulatory Support Therapy With HeartMate 3

MR = Mitral regurgitation

MS = Mitral stenosis

MV = Mitral valve

PA = Pulmonary artery

PET = Positron emission tomography

PFO = Patent foramen ovale

PI = Pulsatility index

POCUS = Point-of-care ultrasound

PR = Pulmonary regurgitation

PV = Pulmonic valve

PW = Pulsed-wave

RA = Right atrial/atrium

RAP = Right atrial pressure

RCA = Right coronary artery

rpm = Revolutions per minute

RV = Right ventricular/ventricle

RVAD = Right ventricular assist device

RVEF = Right ventricular ejection fraction

RVF = Right ventricular failure

RVOT = Right ventricular outflow tract

SVC = Superior vena cava

TEE = Transesophageal echocardiography

TGA = Transposition of the great arteries

TMCS = Temporary mechanical circulatory support

TR = Tricuspid regurgitation

TS = Tricuspid stenosis

TTE = Transthoracic echocardiography

TV = Tricuspid valve

UEA = Ultrasound-enhancing agent

VA = Veno-arterial

VSD = Ventricular septal defect

VTI = Velocity-time integral

VV = Veno-venous

LEFT VENTRICULAR ASSIST DEVICE TYPES

End-stage HF is a clinical syndrome defined by refractory symptoms and signs of HF with significantly decreased functional capacity, despite the use of guideline-directed medical therapy. Left ventricular assist devices have emerged as safe and effective therapy for selected end-stage HF patients, with >27,000 patients having received an LVAD implant based on the most recent Interagency Registry for Mechanically Assisted Circulatory Support (INTERMACS) report. Left ventricular assist device implant volume peaked in 2019, with 3,222 LVADs implanted. There was a drop in yearly LVAD implant volumes in 2020 (2,671 implanted) due to both the effects of the COVID-19 pandemic on cardiac surgical volumes and the 2018 heart transplant allocation policy change in the United States.[5]

The HM3 is currently the only durable LVAD approved by the US Food and Drug Administration available for use in adults. The HM3 was approved for short-term hemodynamic support as a bridge to transplantation in 2017 and for long-term destination therapy in 2018.[6,7] Approval of HM3 was based on results of the Multicenter Study of MagLev Technology in Patients Undergoing Mechanical Circulatory Support Therapy with HeartMate 3 (MOMENTUM 3), a large randomized clinical trial.[7] MOMENTUM 3 enrolled advanced HF patients needing either a bridge to transplantation or destination therapy and compared the HM3 against the established HM-II. The improved HM3 technology, associated with increased hemocompatibility, proved to be superior to the HM-II regarding survival free of disabling stroke or reoperation to replace or remove a malfunctioning device. Based on these improved outcome observations, HM3 utilization has increased and accounted for 99.8% of all LVADs placed in the United States in 2022.[8]

Similar to both the HM-II and the HVAD, the HM3 consists of 3 components in series: (1) an inflow cannula positioned in the left ventricle (LV) near the apex, (2) a mechanical impeller, and (3) an outflow graft anastomosed to the ascending aorta (Figure 1). In contrast to the HM-II (axial impeller with blood flow entering and leaving parallel to the impeller) and like the HVAD, the HM3 impeller is centrifugal (blood enters and leaves the impeller at a 90° angle). Echocardiography allows direct visualization of the proximal inflow cannula, portions of the distal outflow graft, and frequently the outflow graft-to-aorta anastomosis site, but not of the mechanical impeller. Like the HVAD, the HM3 can be implanted within the pericardial sac, whereas the HM-II is implanted in the preperitoneal space below the diaphragm. All current durable LVADs are powered by a driveline connected to an extracorporeal controller (Figure 1). In addition to serving as a power source, the controller continually measures and calculates several parameters related to LVAD function. When these parameters fall outside of predetermined normal ranges, the controller alerts the patient and the HF team that there is a problem. The implications of controller alarms for echocardiography are further discussed below.

TEMPORARY MECHANICAL CIRCULATORY SUPPORT DEVICE TYPES

Cardiogenic shock (CS) is a state of critical end-organ malperfusion accompanied by severe cellular and metabolic impairment as a clinical expression of circulatory failure due to left, right, or biventricular failure. It can be due to acute ischemic or nonischemic events or progression of long-standing cardiac disease or may occur unexpectedly following cardiac surgical procedures (postcardiotomy).[9,10] While the mainstay of CS treatment includes vasopressor and inotropic support, in the past decade, advances in pump technology and design, as well as miniaturization of cannulas, have enabled the advent of several different TMCS types to mitigate some of the adverse systemic effects of prolonged vasopressor and inotropic medical therapy.

The main indications for initiation of TMCS include (1) to treat refractory CS of different etiologies, including post–myocardial infarction, acute-on-chronic HF, postcardiotomy shock, and acute pulmonary embolism, (2) to provide circulatory support during high-risk procedures, including valvular and coronary interventions or complex catheter ablations for arrhythmias, and (3) to promote myocardial recovery with LV unloading.[9,10] These indications are further detailed in Table 1.

Temporary MCS devices can be deployed centrally (via sternotomy or thoracotomy), peripherally (via surgical vascular cutdown), or percutaneously. Percutaneous LV support TMCS devices include the intra-aortic balloon pump (IABP), Impella (Abiomed) devices (Figure 2), TandemHeart (TandemLife, LivaNova; Figure 3), and veno-arterial (VA) extracorporeal membrane oxygenation (ECMO; Figure 4), which can also provide right ventricular (RV) support. Some of these percutaneous devices can be placed by surgical cut-down (Table 1). Percutaneous RV support devices include VA ECMO, the Impella RP Support System (Figure 5) and Impella RP Flex with SmartAssist, and the ProtekDuo cannula (LivaNova) coupled with a centrifugal-flow pump like the TandemHeart (TandemLife) or Rotaflow (Getinge; Figure 5). Percutaneous LV and RV support devices can be

combined to provide biventricular TMCS (Figure 6). Although less commonly used compared to the percutaneously placed TMCS devices, temporary surgically placed support devices for either LV and/or RV support use of extracorporeal centrifugal pumps such as the CentriMag (Abbott; Figure 7) and Rotaflow centrifugal pump (Getinge). Extracorporeal membrane oxygenation can also be deployed for respiratory support only as veno-venous (VV) ECMO (Figure 4). A comparison of features of the current Food and Drug Administration–approved TMCS devices is shown in Table 1. Additional information regarding the different types of TMCS can be found in the Supplemental Material.

Because of the many potential ECMO and other TMCS configurations, combinations, and access sites, image interpretation can be difficult without adequate device placement information. Sonographers should routinely annotate the support type, the associated vascular access sites, and the flow settings (if appropriate) at the study outset, especially when adjusted during an exam. The MCS teams should consider ways to facilitate imagers' ability to readily access such information at the bedside to facilitate workflow.

Key Points: LVADs and Temporary MCS Types

- The HM3 (Abbott) is a continuous-flow (CF) LVAD similar to the HM-II (Abbott) and HVAD (Medtronic) with 3 intracorporeal components: an LV inflow cannula, a mechanical impeller, and an outflow graft that is anastomosed to the ascending aorta.
- The HM3 impeller uses centrifugal flow (blood enters the impeller at a right angle and is propelled outward) like the HVAD versus axial flow (blood flow enters and leaves parallel to the impeller) like the HM-II.
- The HM3 has replaced the HM-II and currently is the only LVAD being implanted based on superior clinical outcomes.
- Temporary MCS devices can be deployed centrally, via sternotomy or thoracotomy, or percutaneously.
- Left- and right-sided devices can be used together to provide biventricular support.
- Sonographers (and all imagers) should understand the TMCS type(s), access sites, and flow settings and annotate this information on the acquired images.

THE ROLE OF ECHOCARDIOGRAPHY IN CANDIDATE SELECTION FOR LVADS

As defined in the 2015 Guideline, optimal candidate selection for the HM3, similar to the HM-II and HVAD, remains an important determinant of successful operative and long-term outcome. The preimplantation echocardiogram in LVAD candidates should include all the elements of a comprehensive examination as recommended by the ASE, with a continued focus on high-risk or "red flag" findings as detailed below and summarized in Table 2. The meaning of a red flag is to draw attention to specific echocardiographic findings or lesions that may interfere with normal device functioning and/or have been associated with increased morbidity and/or mortality post-LVAD implantation. Similar to reports for HM-II and HVAD recipients, these findings include a relatively smaller LV, a larger RV with decreased RV systolic function, intracardiac clot, preexisting valve pathology, and underlying congenital heart disease. For a detailed discussion regarding ventricular dimensions and function assessment, we refer readers to the 2015 Guideline.[3]

Left Ventricular Size and Function Pre-LVAD Implantation

Demonstration and documentation of an LV ejection fraction (LVEF) <25% remains part of the Centers for Medicare and Medicaid Services qualifying selection conditions for LVAD implantation. Recent work supports the previously defined concept that a relatively smaller LV cavity pre-LVAD placement may add technical challenges to the implantation procedure and increases the risk of right HF and suction events.[11] An analysis from the MOMENTUM 3 trial including 2,200 HM3 LVAD patients guided the development of a HM3 risk score based on 6 components to accurately predict 1- and 2-year survival after HM3 LVAD implantation.[11] A small LV size prior to implantation, LV internal dimension at end-diastole (LVIDd) <5.5 cm, was one of the 6 risk factors for mortality (Table 2). This LV size cutoff is smaller than the 6.3 cm cutoff derived from a limited single-center examination that demonstrated an association with increased 30-day morbidity and mortality in 83 patients supported by the HM-II.[12] Other registry-based studies have also demonstrated that a larger LV is associated with an improvement in post-LVAD implantation survival.[13]

Defining and Predicting RVF After LVAD Implantation

Late RV failure (RVF), in contrast to early RVF within 30 days post-LVAD, has emerged as an important clinical syndrome following LVAD placement. Although the definition of late RVF has been somewhat variable, it is generally recognized to be a syndrome of right HF requiring an intervention (i.e., inotrope or right-sided device support) occurring >30 days after LVAD implantation.[14,15] Late RVF is associated with worse quality of life, poorer functional capacity, increased readmissions, and worse survival.[14,16] Based on one study, a pre-LVAD tricuspid valve (TV) annulus diameter ≥41 mm, a surrogate of RV remodeling, was reported to be associated with late RVF.[17]

Based on the MOMENTUM 3 trial, the prevalence of any RVF, defined according to symptoms and signs, including RV assist device (RVAD) use or prolonged inhaled nitric oxide or inotrope use, was similar in patients supported by the HM-II and HM3 (28% vs 34%).[2] In a meta-analysis of observational studies of risk factors associated with early RVF after LVAD implantation,[18] preimplantation moderate-to-severe RV dysfunction assessed qualitatively or a larger RV/LV diameter ratio were the echocardiographic measurements associated with good prediction of RVF post-LVAD implantation. Based on this meta-analysis, the RV/LV diameter ratio, obtained by measuring the RV and the LV sizes from the apical 4-chamber and parasternal long-axis views, respectively, was deemed the single most significant quantitative echocardiographic measurement able to define risk of RVF in LVAD recipients (Figure 8). This meta-analysis observation was based on only 4 studies, with the largest study including 109 patients supported by the HM-II. Based on this study, an RV/LV diameter ratio ≥0.75 was independently associated with a higher risk of RVF.[19] Validation studies using the RV/LV diameter ratio along with the proposed cutoff value to predict RVF in patents supported by the HM3 are lacking.

The role of RV strain imaging before LVAD implantation has also been further explored. Recent studies have demonstrated the incremental value of RV strain analysis in predicting RVF.[20,21] Although

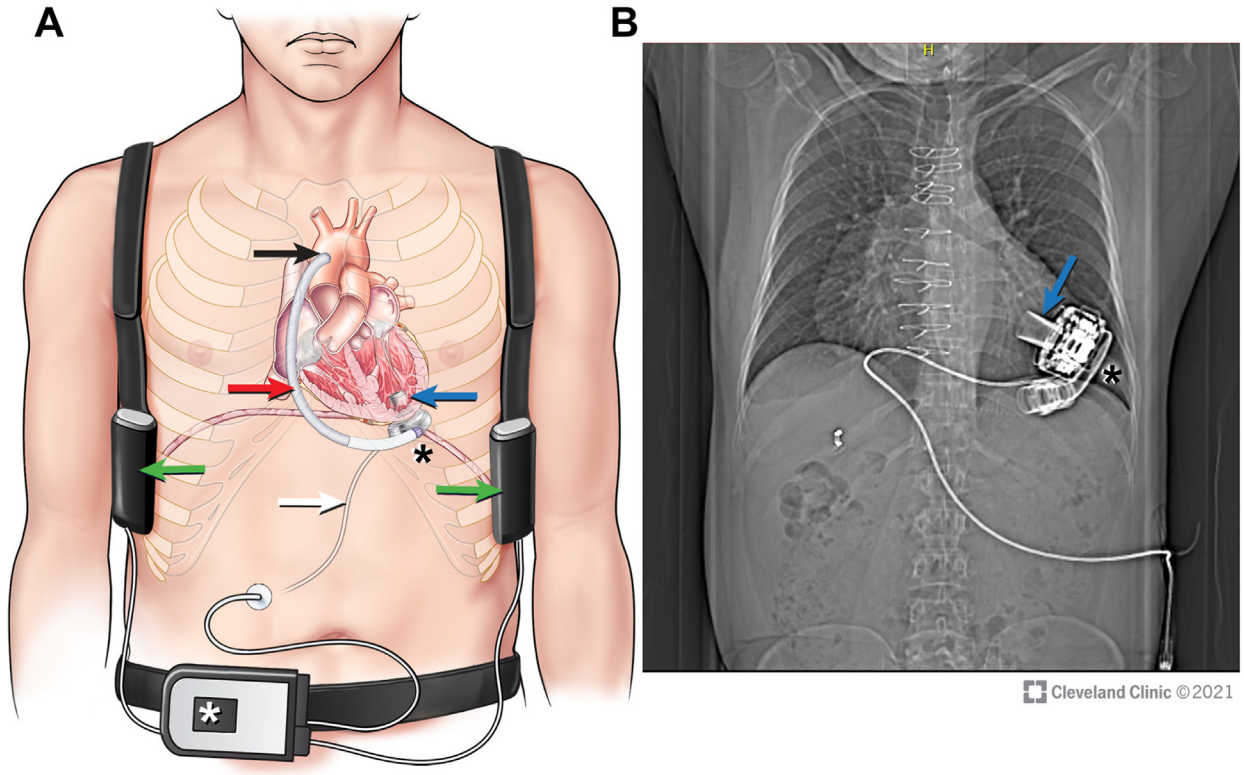


Figure 1 HeartMate 3 LVAD. **(A)** Drawing showing the intrapericardial pump location and impeller housing (*black asterisk*), inflow cannula (*blue arrow*), right parasternal outflow graft position (*red arrow*), and outflow graft–to–ascending aorta anastomosis (*black arrow*). The *white arrow* shows the driveline that is connected to the extracorporeal controller (*white asterisk*) that permits delivery of power to the devices. *Green arrows* show the battery packs. **(B)** An x-ray CT scout image showing the anatomic relationship between the LV and the device inflow cannula (*blue arrow*) and impeller housing (*black asterisk*).

analysis of RV strain mechanics remains a promising technique, limited ultrasound imaging windows may not permit accurate speckle-tracking analysis in all patients.

Measures of RV systolic function such as RV ejection fraction (RVEF) and indexed RV end-diastolic and end-systolic volumes by three-dimensional (3D) echocardiographic assessment have emerged as predictors of early RVF after LVAD placement; however, the evidence is limited.[22,23] Whenever technically feasible, calculation of RV volumes and RVEF by 3D echocardiographic assessment should be considered. The writing group appreciates that this approach can be technically challenging and not readily available.

Key Points: LV and RV Function and LVAD Patient Selection Consideration

- Documenting LVEF <25% remains part of the Centers for Medicare and Medicaid Services–qualifying LVAD selection condition.
- A small LV size (LVIDd <5.5 cm) is associated with increased mortality after HM3 LVAD implantation.
- The prevalence of RVF after LVAD implantation in patients supported by the HM3 is similar to other CF LVADs.
- In addition to severe RV systolic dysfunction, defined qualitatively or quantitatively, the RV/LV ratio (e.g., >0.75), obtained from the apical 4-chamber and parasternal long-axis views, is among the most definitive quantitative echocardiographic measurements to help define the risk of RVF after LVAD placement.
- Recent studies have demonstrated the incremental value of RV strain analysis and measures of RVEF and indexed RV end-diastolic and end-systolic volumes by 3D echocardiography in predicting RVF.

Valve Disease and LVAD Implantation

We refer readers to the 2015 Guideline document that addressed detection and quantitation of valvular regurgitation, valvular stenosis, and prosthetic valve dysfunction and the importance of these abnormalities in patients being considered for LVADs.[3,24] Surgical treatment of more than mild aortic regurgitation (AR) should be addressed at the time of LVAD implant and remains a standard practice recommendation that applies to the HM3 device.[25] In contrast to AR, aortic stenosis (AS) is typically well tolerated during LVAD support and, thus, does not typically require concomitant intervention. Aortic stenosis of any degree that is accompanied by more than mild AR should prompt consideration for a bioprosthetic aortic valve (AV) replacement during MCS implant.[25]

In contrast to the 2015 Guideline stance that any degree of mitral regurgitation (MR) is acceptable in LVAD candidates,[3] more recent observations highlight severe MR (Figure 9) as a potential red flag prior to LVAD use, given the association of persistent severe MR with poorer

Table 1 Temporary mechanical circulatory support device types and clinical applications

	Inflow/outflow/pump placement	Clinical applications and characteristics
IABP	Percutaneous or surgical cut-down (Femoral, subclavian, or axillary artery)	LV support Diastolic inflation: improves cerebral and coronary perfusion Systolic deflation: increases LV unloading, decreases LV wall stress and myocardial oxygen consumption
TandemHeart (Tandem Life)	Centrifugal extracorporeal LA-to-femoral/axillary artery Percutaneous or surgical cutdown	LV support Placed under fluoroscopic and echocardiographic guidance Requires transseptal puncture
ProtekDuo (Tandem Life)	Centrifugal extracorporeal Inlet: SVC-RA junction Outlet: PA Percutaneous (right IJ vein)	RV support Can be combined with an external membrane oxygenator for respiratory support Spectrum Medical dual lumen coaxial cannula for RV support is similar to ProtekDuo with an additional drainage port in the RV
Impella CP (Abiomed) Impella 5.5	Microaxial intracorporeal LV-to-ascending aorta Impella CP: percutaneous (femoral artery) Impella 5.5: surgical cutdown (axillary artery) or direct aortic	LV support Hemodynamic benefits: Increased cardiac output Unloading of the LV: lower LV filling volume and pressure, decreased wall stress and myocardial consumption
Impella RP	Microaxial intracorporeal Inlet: IVC-RA junction Outlet: PA Percutaneous (femoral vein)	RV support Pulls blood from the RA and pumps it into the PA
Impella RP Flex	Microaxial intracorporeal Inlet: SVC- RA junction Outlet: PA Percutaneous (right IJ vein)	RV support Pulls blood from the RA and pumps it into the PA
Surgically implanted TMCS: Centrimag (Thoratec Corporation) Rotaflow (Maquet Getinge Group) Bio-Pump (Medtronic)	Extracorporeal centrifugal LV support: LA/LV-to-ascending aorta RV support: RA/RV-to-PA Surgical sternotomy or thoracotomy	LV, RV, or biventricular support Possible biventricular support configurations: Durable LVAD and surgically implanted RV TMCS Surgically implanted LV and RV TMCS
VA ECMO	Extracorporeal centrifugal with membrane oxygenator RA-to-ascending aorta/descending aorta Central: sternotomy or thoracotomy Peripheral: percutaneous and/or surgical cutdown	LV, RV, or biventricular support additional configurations VVA: third venous cannula for improved venous drainage Veno-arterial-venous: oxygenated blood is returned to both the ascending aorta and the RA Veno-arterial-arterial : 2 separate cannulas return oxygenated blood to the arterial system (e.g., descending aorta and axillary artery)
VV ECMO	Extracorporeal centrifugal with membrane oxygenator Dual vein cannulation: drainage from the IVC (via femoral vein) with return in the RA (via femoral vein and IVC or right IJ and SVC) Single vein cannulation: dual lumen single cannula with drainage from SVC and IVC and return in the RA	Respiratory support: VV ECMO does not provide direct circulatory support, may improve RV function through respiratory support

CP, Cardiac power; *VVA*, Veno-veno-arterial.

post-LVAD outcome (Figure 9, Table 2). Recent studies have demonstrated that for patients with significant functional MR undergoing concomitant mitral valve (MV) repair at the time of LVAD implantation, there is an improvement in quality of life and functional status, reduction in the incidence of late RVF, and a reduced rate of hospital readmission.[26-28] In addition, residual MR after LVAD implantation has been associated with persistent postimplantation pulmonary hypertension, increased risk of RVF and renal failure, and a trend toward increased mortality.[29] Kanwar *et al.* reported on 927 patients undergoing HM3 LVAD implantation without a prior or concomitant MV procedure.[30] In this cohort, 403 (43.5%) had clinically significant moderate to severe MR at baseline, highlighting that significant MR is

frequently present at the time of LVAD implantation. Following 1 month of HM3 device support, residual MR was present in only 6.2% of patients and at 2 years, MR resolved in most patients with HM3 support. In contrast to other reports, the presence or absence of baseline MR did not influence overall survival, rate of major adverse events, or functional capacity. Severe MR at baseline, larger LV dimension, and implantation with the HM-II device instead of the HM3 were independently associated with an increased likelihood of persistent MR following LVAD implantation. Although stronger evidence is still needed to determine whether residual MR adversely impacts LVAD outcomes, particularly mortality, echocardiography can help identify patients at risk for residual MR. Based on recent guidelines, concomitant MV interventions may be considered in patients with severe MR during LVAD implantation with consideration of MV repair or replacement using a bioprosthetic valve.[25]

Mitral stenosis (MS) remains infrequently encountered in patients undergoing LVAD evaluation. However, significant MV stenosis, defined as greater than moderate severity, may be encountered in patients with a history of multiple transcatheter edge-to-edge repairs. Based on current recommendations, significant MS needs to be addressed during LVAD implantation due to concern that MS limits LVAD filling and maintains left atrial (LA) and pulmonary hypertension.[25] Commissurotomy or MV replacement using a bioprosthetic valve can be performed; however, the use of a mechanical valve is not recommended due to the risk of thromboembolic complications.[25]

As stated in the 2015 Guideline,[3] moderate or greater tricuspid regurgitation (TR) remains a potentially ominous finding. Consensus regarding the management of more than moderate TR at the time of LVAD implantation still does not exist.[25] Current guidelines state concomitant TR interventions may be considered during LVAD implantation in patients with greater than moderate TR and TV repair or replacement using a bioprosthetic valve can be performed.[25] Optimal candidate selection should use a combination of clinical and echocardiographic parameters to identify select patients that may benefit from concurrent TV repair or replacement at the time of LVAD implantation.

Key Points: Valve Disease and LVAD Patient Selection Considerations

- A comprehensive pre-LVAD implantation assessment of the AV, MV, and TV anatomy and function should be performed.
- Surgical treatment of AR greater than mild severity before LVAD implantation remains a recommendation for HM3 implantations.
- AS is well tolerated during LVAD support and does not typically require concomitant intervention.
- Severe MR prior to HM3 implantation is associated with an increased likelihood of persistent MR following LVAD implantation and has been added to the red flag pre-LVAD implantation high-risk findings.
- Mitral stenosis (moderate or greater) may prevent adequate LVAD filling and may need to be addressed at the time of LVAD implantation.
- Tricuspid regurgitation remains a red flag before HM3 placement, although there remain mixed data regarding the benefits of concurrent TV repair or replacement at the time of LVAD implantation.

Congenital Heart Disease High-Risk Findings

Current use of LVADs in patients with adult congenital heart disease (ACHD) remains low at <1% of LVADs placed.[31] A few centers have reported LVAD placement in the systemic ventricle regardless of the underlying ventricular morphology. Examples include placing an LVAD in a patient with a systemic morphologic RV (l-transposition of the great arteries [TGA] and d-TGA status after an atrial switch procedure) or a systemic morphologic LV (e.g., d-TGA after an arterial switch procedure or l-TGA status after a double switch procedure, common AV canal, or tetralogy of Fallot).[31,32] Although survival in selected ACHD patients supported by an LVAD is reported to be similar to survival of patients without underlying ACHD and supported by an LVAD, these observations come from a relatively small number of patients.[31] Patients with ACHD have higher rates of complications. Therefore, complex ACHD lesions, as defined in the American College of Cardiology ACHD guideline,[33] should continue to be viewed as red flag signs.[31]

Ancillary Imaging to Define Other High-Risk Findings Prior to LVAD Implantation

Preoperative CT Imaging. Routine preoperative CCT with contrast (CT angiography [CTA]) or CCT without contrast in patients undergoing surgical LVAD implantation who have a history of prior cardiac surgery can assist operative planning and potentially reduce the risk of stroke and mortality.[34] Cardiovascular structures, including bypass grafts, ideally should be located >10 mm from the sternum in patients with a history of a prior sternotomy. Table 2 lists red flags defined by CT imaging prior to LVAD placement. Although a minimally invasive surgical approach to place contemporary LVADs may offer several benefits, including a lower 30-day mortality rate compared to a conventional sternotomy, a traditional sternotomy remains the most commonly used approach, highlighting the importance of assessing reentry as part of the procedure planning.[35]

Key Points: Red Flags in Candidate Selection for LVADs

- All LVAD candidates should undergo preoperative echocardiography, as defined in Table 2, to screen for structural and/or functional abnormalities that may preclude LVAD implantation or that may alter surgical planning.
- In patients with ACHD, echocardiography, CT, and magnetic resonance imaging may be complementary modalities to define the underlying anatomy and to screen for lesions that may pose significant challenges before LVAD implantation.
- CT imaging (either noncontrast or CTA) is clinically useful by assisting in operative planning in patients undergoing repeat sternotomies.

THE ROLE OF ECHOCARDIOGRAPHY IN CANDIDATE SELECTION FOR TEMPORARY MCS

For all TMCS support selections, similar to candidate selection for durable LVAD placement, echocardiography is used to confirm the need for device placement, guide understanding of RV support needs, and

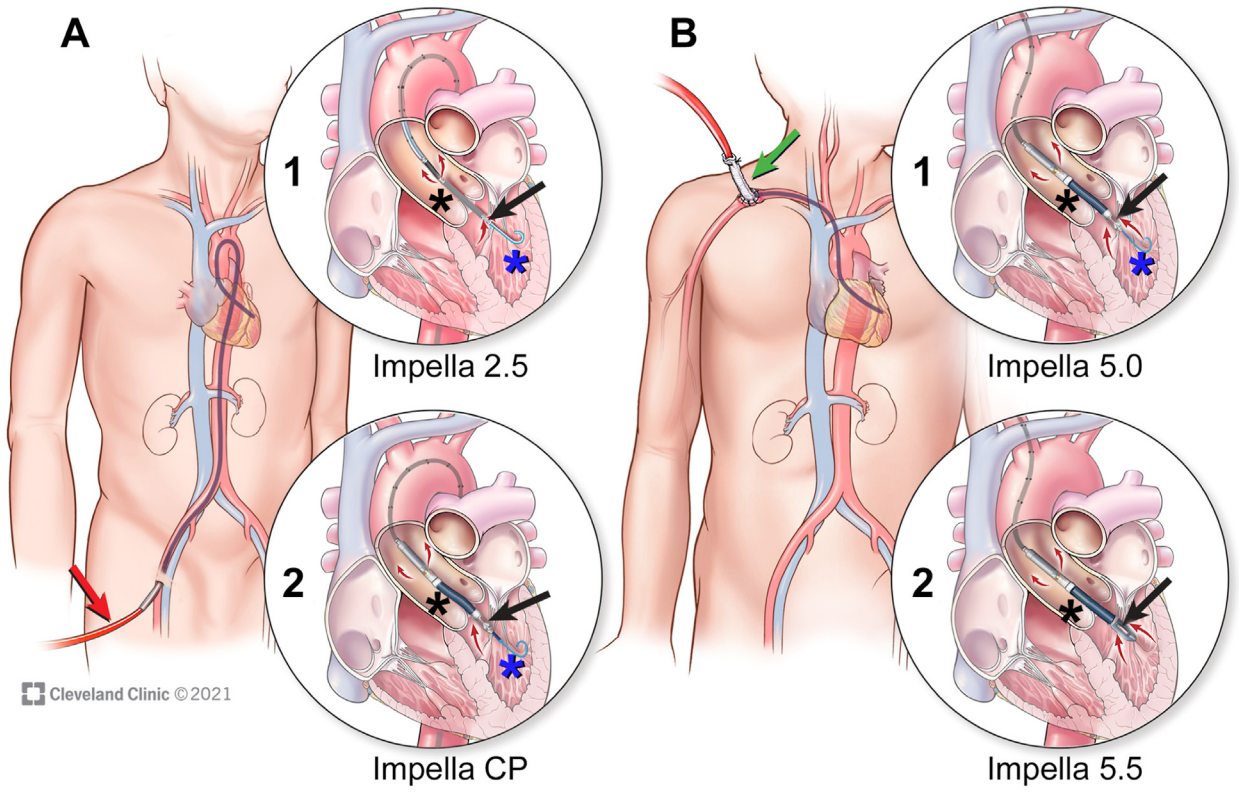


Figure 2 Impella devices. **(A1)** Drawing showing the Impella 2.5 and **(A2)** Impella CP placed using the femoral artery (*red straight arrow*). **(B1)** Impella 5.0 and **(B2)** Impella 5.5 placed using a graft (*green arrow*) in the right axillary artery. The *black arrow* shows the inlet of the device where blood enters and is propelled from the LV into the ascending aorta (*curvilinear red arrows*). The *blue asterisk* marks the flexible pigtail, which is a component of the Impella 2.5, CP, and 5.0 devices but is not a component of the Impella 5.5. The *black asterisk* marks the motor housing containing the microaxial rotor and the outlet just beneath the motor housing that permits exit of the propelled blood from the LV. Of note, Impella 2.5 and 5.0 have been phased out of manufacturing. The only Impella devices currently in use are CP and 5.5.

rule out the presence of lesions that may interfere with device functioning or are associated with increased complications. In addition, echocardiography can be used to confirm the correct placement of the cannulas, monitor the degree of ventricular unloading, troubleshoot device low flow during support, monitor for myocardial recovery, and, in conjunction with hemodynamics, assess the potential for weaning and removing TMCS.

Similar to candidate selection for LVADs, the preimplantation echocardiogram should include all the elements of a comprehensive echocardiographic examination recommended by the ASE guidelines.[36,37] However, given the urgent need of deployment of these devices, an exam focused on specific conditions and findings that may alter the deployment plan may be an up-front necessity. Echocardiographers should be familiar with the absolute and relative contraindications for each device (Table 3) so that this information is readily available to the MCS team. In the absence of absolute contraindications, special attention should be given to red flag findings, which, while not representing an absolute contraindication to placement of the device, may interfere with its proper positioning and function.

Temporary LV Support Devices and Patient Selection Considerations

Patients with CS should have a transthoracic echocardiogram (TTE) to guide selection considerations based on intracardiac findings. Transesophageal echocardiography (TEE) is recommended when TTE is nondiagnostic and to guide device placement. Vascular ultrasound is not routinely needed to assess cannulation sites prior to device placement. Preimplantation red flag findings for temporary LV support are summarized in Table 3. Additional considerations are presented below.

Intra-aortic Balloon Pump and Selection Considerations. Detailed description of echocardiography-guided placement of the IABP has been presented in recent ASE guidelines.[37] Briefly, the preinsertion examination should document any contraindications to the use of an IABP such as the presence of greater than mild AR. Aortic pathology such as aortic dissection or mobile atheromatous disease should also be excluded (Table 3).

Impella Left-Sided Support Devices and Selection Considerations. A small LV chamber, a narrow LV outflow tract (LVOT) due to the presence of asymmetric septal hypertrophy, or any other form of subaortic obstruction may preclude the placement of the device or make its positioning challenging. Similarly, a redundant, myxomatous MV may lead to obstruction of the inlet of the device.[38] Left ventricular apical thrombi represent additional red flags that may create challenges or increase thromboembolic risk with device placement (Table 3). While the presence of severe AR does not preclude the placement of the device, its presence may result in

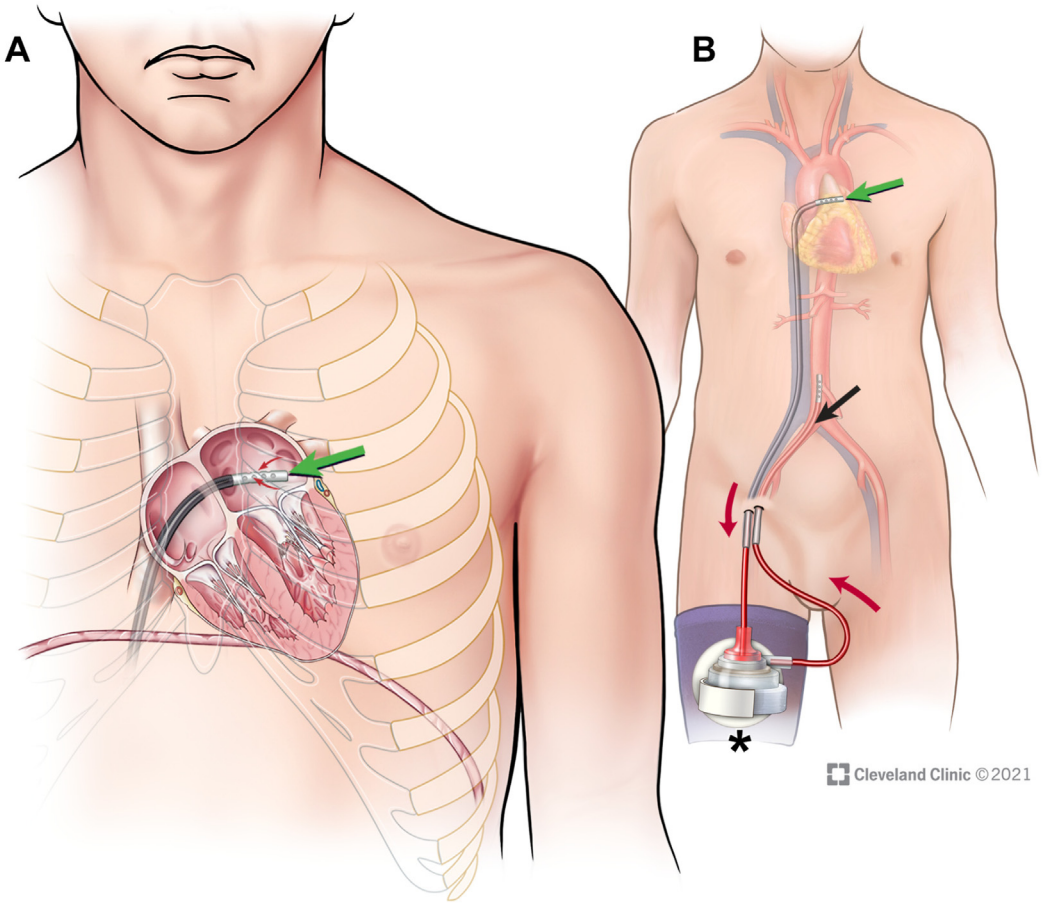


Figure 3 TandemHeart. **(A)** Drawing showing a 21F inflow cannula (*green arrow*) positioned in the LA. **(B)** Blood is returned to the extracorporeal centrifugal pump (*black asterisk*) and propelled to the iliac artery by way of the femoral artery (*black arrow*). *Curvilinear red arrows in panel B* mark the blood flow direction generated by the pump.

ineffective LV emptying and decreased forward flow due to recirculation. Severe AS has traditionally been considered a relative contraindication; however, there are a few reports of the safe use of this device in the presence of severe AS.[39] The presence of a mechanical prosthetic AV is a contraindication to the placement of device.

TandemHeart Selection Considerations. The presence of LA thrombus is a potential contraindication for the placement of TandemHeart (Table 3). However, the placement of this device does not involve access to the LV or the ascending aorta or transvalvular access across the AV; therefore, it can be deployed in patients with LV thrombus, ventricular septal defect (VSD) after myocardial infarction, severe AS, significant AR, mechanical prosthetic AV, or significant atherosclerotic disease of the ascending aorta.[40]

Temporary RV Support Devices and Patient Selection Considerations

Before all RV TMCS device deployments, the presence of thrombus and other masses in the right atrium (RA) or the pulmonary artery (PA) should be excluded by TEE or TTE, as they may interfere with cannula placement and flow. The presence of significant intracardiac shunts (e.g., large patent foramen ovale [PFO], atrial septal defect [ASDs], and VSDs) should also be ruled out, as these may result in worsening left-to-right shunting with RV unloading (Supplemental Figure 3). Preimplantation red flag findings for temporary RV support are summarized in Table 3.

The presence of strictures or thrombi in the superior vena cava (SVC) and/or inferior vena cava (IVC) can preclude the placement of these devices and can impede adequate distal venous drainage. Additional contraindications to placement of an Impella RP are the rare presence of a congenitally interrupted IVC[41] and the presence of an IVC filter. Tricuspid valve and pulmonic valve (PV) function should be assessed using two-dimensional (2D) echocardiography, color-flow Doppler (CFD), and spectral Doppler. The presence of mechanical TV or PV prostheses, as well as severe TV or PV stenosis, preclude placement of these devices. While significant TR is typically well tolerated during support, the presence of more than mild pulmonic regurgitation may limit the efficacy of device flow delivered to the PA. Increasing transpulmonary flow with an RV TMCS in the presence of an already elevated LA pressure (LAP), due to uncorrected left heart disease, may increase the risk of pulmonary edema. In these situations, biventricular support or VA ECMO should be considered.

Extracorporeal Membrane Oxygenation and Patient Selection Considerations

Important pathologies and anatomical findings relevant to the deployment of ECMO are summarized below and in Table 4.

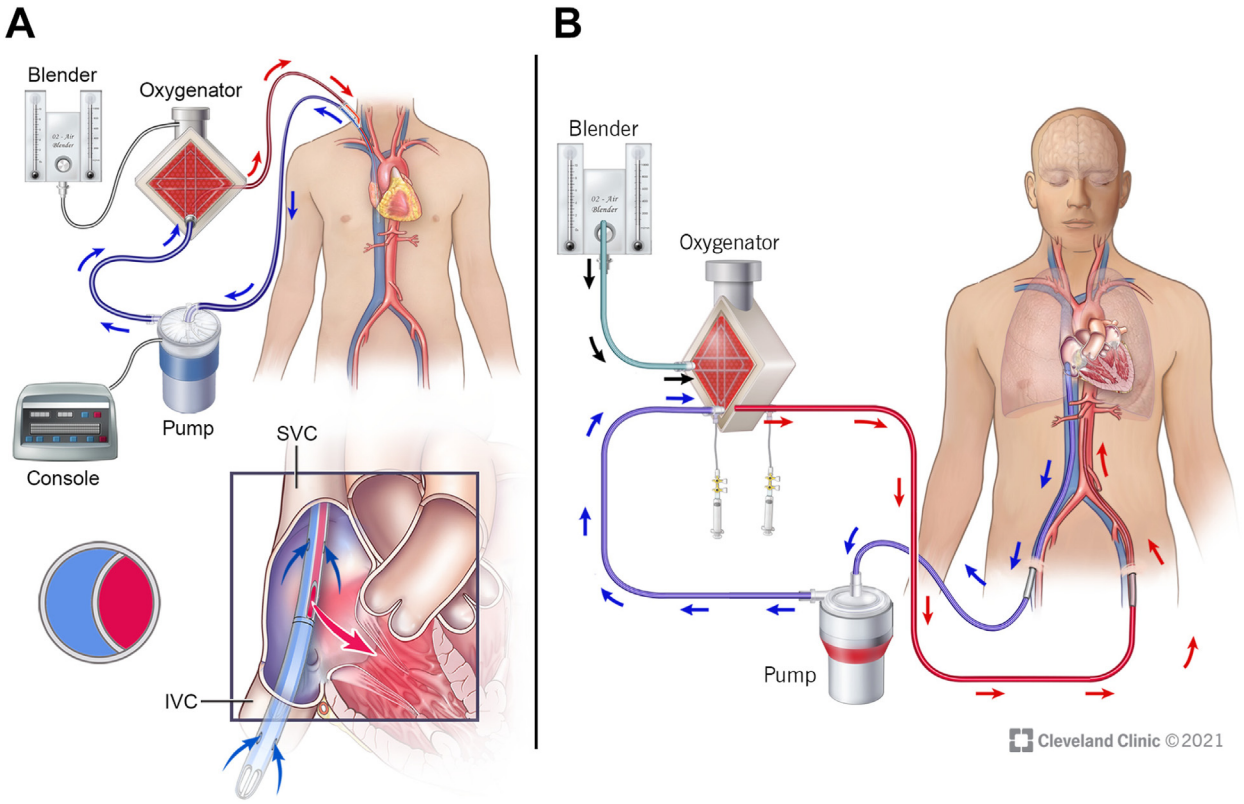


Figure 4 Veno-venous and VA ECMO. **(A)** Drawing showing VV ECMO using a dual lumen cannula from the right IJ vein. *Blue arrows* show the direction of deoxygenated blood from the superior and IVC drawn to the centrifugal pump to the oxygenator with return of oxygenated blood (*red arrows*) back to the distal RA just above the TV. **(B)** Peripheral VA ECMO. *Blue arrows* show the direction of deoxygenated blood from the RA to the centrifugal pump to the oxygenator with return of oxygenated blood (*red arrows*) to the iliac artery by way of the femoral artery.

Echocardiographic examination pre-ECMO deployment should (1) confirm the presence of left, right, or biventricular dysfunction, (2) exclude new pathology amenable to urgent surgical intervention as the cause of hemodynamic collapse (e.g., pericardial effusion with cardiac tamponade, ventricular free wall rupture, severe MR due to papillary muscle rupture), (3) exclude contraindications to deployment of VA ECMO, such as aortic dissection, or moderate or severe AR, and (4) exclude relative contraindications to deployment of VV ECMO alone, such as severe RV and/or LV dysfunction (which would require a higher level of support) or acute cor pulmonale and/or PA emboli.

A problem-focused echocardiographic exam (TTE or TEE) of the RA should be performed to identify previously implanted devices or structural abnormalities that may interfere with adequate positioning or function of the cannulas. Concerning RA findings include an aneurysmal or hypermobile atrial septum, atrial septal communications (ASD or a large PFO tunnel defect), prominent Chiari network, masses, pacemaker, implantable defibrillator leads, and chronic indwelling catheters. Transesophageal echocardiography may be needed if an ASD (in particular a sinus venosus ASD) is suspected. Similar to the RV support devices, stenosis of the IVC or SVC, the presence of IVC filters, and congenital abnormalities such as congenitally interrupted IVC[41] and persistent left SVC with absent right SVC variant[42] preclude the placement of cannulas in the venous circulation. For VV ECMO, TV pathology such as tricuspid stenosis (TS) or TV replacement may impede filling of the RV. For VA ECMO, the sites of arterial cannulation (ascending aorta, descending aorta) should be evaluated, if time permits, for the presence of large or mobile atheromas.

Key Points: Temporary Support Device and Patient Selection Considerations

- Echocardiography is used to confirm the need for TMCS placement and rule out the presence of lesions that may interfere with device functioning or are associated with increased complications and therefore are defined as red flags.
- An exam focused on the conditions and findings that may alter the TMCS deployment plan may be an up-front necessity, and echocardiographers should be familiar with the contraindications for each device (Tables 3 and 4).

PERIOPERATIVE TEE FOR DURABLE LVAD

Preimplantation TEE

As stated in the 2015 Guideline,[3] a comprehensive perioperative TEE examination is critically important in the patient undergoing LVAD implantation. The preimplantation TEE focus remains on LVAD cannulation sites (LV apex and aorta), exclusion of hemodynamically

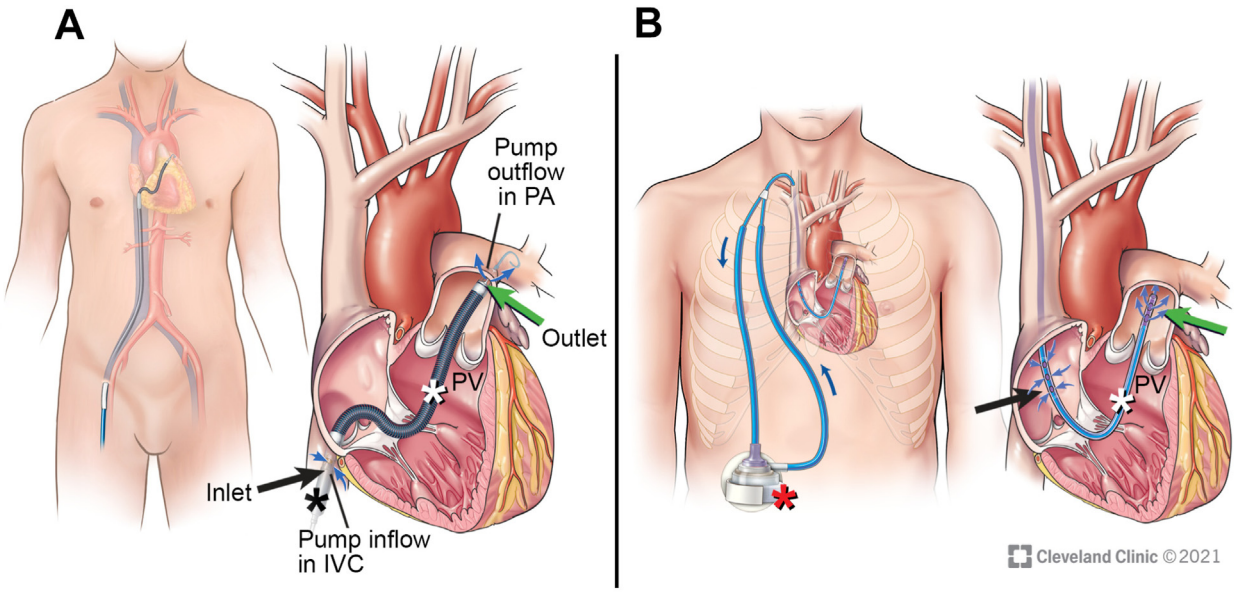


Figure 5 Impella RP and ProtekDuo system. **(A)** Impella RP system catheter in the heart placed via the right femoral vein. Blood is propelled through the inlet (*black arrow*) positioned in the IVC via an encapsulated motor in the motor housing (*black asterisk*) through the 22F catheter (*white asterisk*) to exit above the PV via the outlet (*green arrow*). The distal pigtail is positioned in the PA. **(B)** ProtekDuo cannula in the heart via right IJ vein insertion. Blood is drawn (*curvilinear blue arrows*, *right panel*) into the cannula via drainage holes in the RA (*single black arrow*) and drawn into a centrifugal pump (*red asterisk*) and then propelled in the coaxial dual lumen 29F cannula (*white asterisk*) with delivery above the PV into the PA via the outlet drainage holes (*green arrow*).

significant valve lesions, detection of left atrium (LA), LA appendage (LAA), or LV masses or thrombus, detection of intracardiac shunts, and evaluation of baseline RV function, using recommended views and guidelines.[24,37] A preimplantation TEE checklist should be used by sonographers and/or echocardiographers (Appendix Table 1).

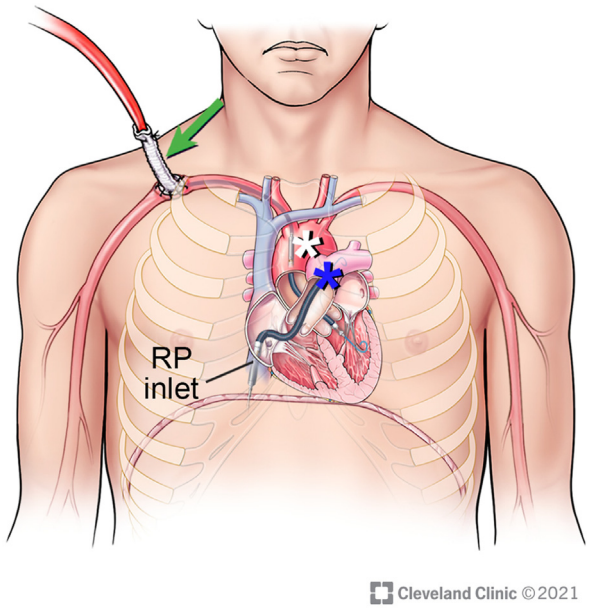


Figure 6 BI-PELLA biventricular support. Drawing showing an Impella 5.5 device placed via a graft (*green arrow*) in the right axillary artery. Blood enters the Impella from the LV and is propelled into the ascending aorta (*white asterisk*). The Impella RP system catheter inlet positioned in the IVC propels blood to above the pulmonary valve (*blue asterisk*). This configuration is referred to as BI-PELLA support.

Transesophageal Echocardiography During LVAD Implantation

Intraoperative TEE aids in the management of a very acutely ill and hemodynamically tenuous patient population before, during, and after the procedure and provides essential information on intra- and postprocedural aspects related to the presence of the device, such as position and flow through the outflow and inflow cannulas. Intraoperatively, TEE can aid in selecting the optimal position of the inflow cannula at the LV apex. This becomes particularly important during LVAD implantation via a thoracotomy approach, which provides only limited visualization of the LV apex. The indentation made by the surgeon's finger to identify the LV apex can be visualized in 2 or more simultaneous LV long-axis views by using multiplane imaging (Figure 10).

Preparation of the insertion site of the inflow cannula by apical coring of the LV is invariably accompanied by some degree of entrained air in the left heart chambers. Air often collects in the nondependent portions of the heart and vessels including the interventricular septum (IVS), LV apex, interatrial septum (IAS), LAA, aortic root, ascending aorta, and pulmonary veins. The ostium of the right coronary artery (RCA) is situated anteriorly in the aortic root. Air bubbles ejected from the LV can preferentially accumulate in the right aortic sinus of Valsalva and embolize to the RCA during cardiopulmonary bypass (CPB) weaning. Acute RV dysfunction or dilatation and/or an increase in the severity of TR should suggest the possibility of air embolization to the RCA. This complication may resolve with increasing systemic pressures and watchful waiting or may require reinstitution of CPB. Deairing maneuvers should be performed under TEE guidance. Left ventricular assist devices can generate negative intraventricular pressure and a suction effect. Therefore, attention should be paid

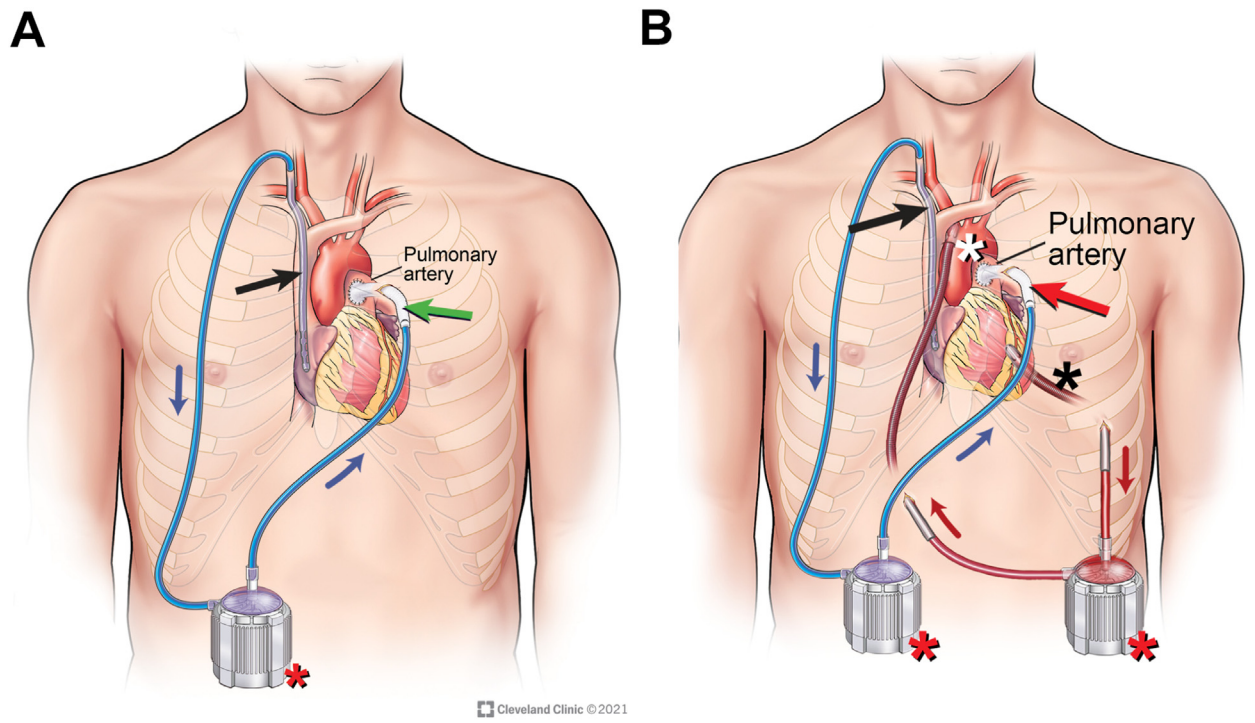


Figure 7 Surgically placed CentriMag ventricular assist system. **(A)** Drawing showing CentriMag RV support with the inlet venous cannula (*black arrow*) positioned in the RA and blood pulled (*blue arrow*) into the centrifugal pump (*red asterisk*) and propelled (*blue arrow*) to the PA (*green arrow*) via the outlet cannula. **(B)** Drawing showing that biventricular surgically placed CentriMag pump with the inlet venous cannula (*black arrow*) is positioned in the RA and blood is pulled (*blue descending arrow*) into the centrifugal pump (*red asterisk*) and propelled (*blue curved arrow*) to the PA (*red arrow*) via the outlet cannula. An inlet cannula is positioned in the LV (*black asterisk*), and blood is drawn into (*red descending arrow*) the centrifugal pump (*red asterisk*) and propelled (*red ascending arrow*) into the ascending aorta via an outflow arterial cannula (*white asterisk*).

not only to removal of intracardiac air but also to the possibility for entrainment of external (ambient) room air into the heart or the circulation from small surgical leaks under negative internal pressure.

Transesophageal Echocardiography During LVAD Activation and Speed Optimization

As mentioned in the 2015 Guideline,[3] it is recommended that immediately after LVAD implantation, a comprehensive TEE exam should be performed based on an established checklist (Appendix Table 1). The pump speed at the time of image acquisition should be annotated on the images or video loops. Assessment of AV opening, the relative LV and RV sizes, degree of TR, ventricular septal position, inflow cannula position, and flow velocities is recommended after initiation of LVAD support and after changes in the LVAD pump speed. Some of the components of the TEE exam unique to the immediate post VAD activation period are highlighted below.

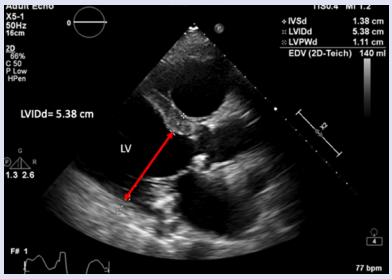
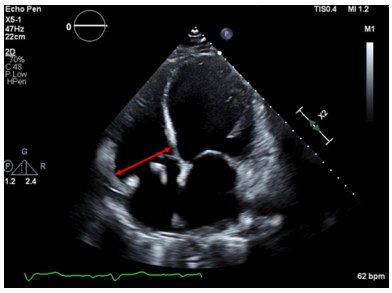
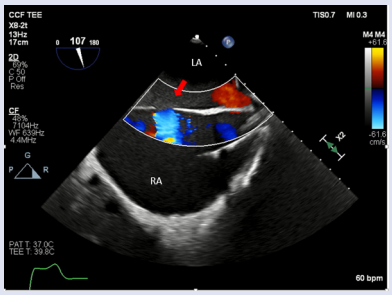
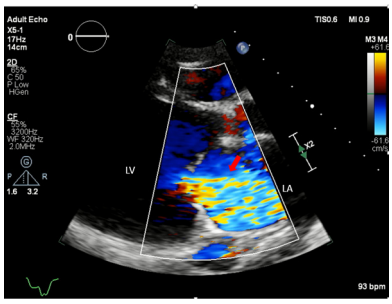
Patent Foramen Ovale Detection. It is important to reevaluate the IAS early after separation from CPB. A PFO may be "unmasked" and detectable only after LVAD implantation. This can occur in 20% of cases where a PFO was undetectable in the preimplantation examination.[43]

HeartMate 3 Flow Characteristics. The HM3 pump has a unique software algorithm that cyclically changes the rotor speed every 2 seconds (30 times/min) resulting in an artificial pulse. The ramp-down in pump speed is by 2,000 revolutions per minute (rpm) below the baseline program pump speed for 0.15 seconds followed by a ramp-up by 4,000 rpm for 0.20 seconds. This characteristic HM3 rotor speed variation pattern results in unique spectral Doppler flow patterns described below.

Inflow Cannula. The LVAD inflow cannula placed in the LV apex should be aligned with the MV opening, away from the IVS and the lateral wall.[44,45] In contrast to the HVAD centrifugal pump where inflow cannula velocities cannot be accurately measured due to a characteristic Doppler artifact, HM3 inflow cannula velocities can be accurately examined by biplane 2D, CFD, and spectral Doppler echocardiography at the midesophageal level (Figure 11). Color-flow Doppler interrogation at the inflow cannula opening should demonstrate low-velocity, unidirectional, laminar flow. In addition, unobstructed flow should be demonstrated using continuous-wave (CW) or pulsed-wave (PW) Doppler from the inflow cannula with peak velocities of 1 to 2 m/sec^3. The artificial pulse of the HM3 device generates periodic higher peak velocities that are not synchronized with the native cardiac cycle (Figures 11 and 12).

Three-dimensional echocardiography provides additional information to cannula imaging. An en face view of the cannula inflow zone, below the MV, allows assessment of the cannula position (ideally coaxial with the LV long axis) and its relationship to other structures such as the IVS and MV (Figure 11). There is no consensus definition of what constitutes LVAD inflow cannula malposition. However, early identification of apparent off-axis positioning of the inflow cannula relative to the ideal apical position, especially if coupled with visualization of the inflow cannula abutting the endocardium (Figure 13) and/or creating ventricular ectopy or LVAD suction alarms (see the

Table 2 Red flag findings on TTE/TEE and CT before durable LVAD implantation

CT findings	Example illustrations
LV and IVS: Small LV size (LVIDd <5.5 cm; see adjacent Figure A, *red double-headed arrow*) LV trabeculation LV thrombus LV apical aneurysm VSD	 Figure A. Relatively small LV size.
RV: RV dilation relative to LV size (see adjacent Figure B, *red double-headed arrow*) RV/LV diameter ratio ≥0.75 RV systolic dysfunction	 Figure B. Dilated RV (see text and movie 1).
Atria, IAS, and IVC: LAA thrombus PFO or ASD (see adjacent Figure C, *red arrow*)	 Figure C. Secundum ASD (see text).
Valvular abnormalities: Any prosthetic valve (especially mechanical MV) >Mild AR ≥Moderate MS >Moderate MR (see adjacent Figure D, *red arrow*) ≥Moderate TR or > mild TS >Mild pulmonary stenosis; ≥moderate PR	 Figure D. Moderate to severe MR.

(*Continued*)

Table 2 (*Continued*)

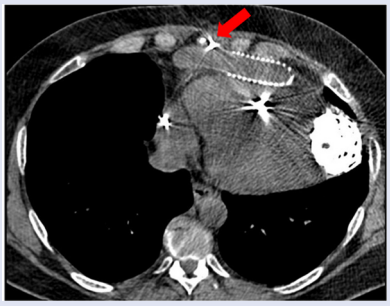
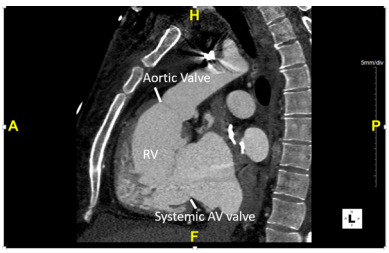
CT findings	Example illustration
Prior sternotomy: Close relationship of cardiovascular structures to the sternum (<10 mm, see adjacent Figure E) Close relationship of coronary bypass grafts to sternum Significant atherosclerotic calcifications of ascending aorta Significant calcification of the aortic arch	 Figure E. Left ventricular assist device outflow graft just underneath the sternum noted prior to redo sternotomy.
Other: Any congenital heart disease (see adjacent Figure F) Aortic pathology: aneurysm, dissection, atheroma, coarctation Mobile mass lesion Other shunts: patent ductus arteriosus, intrapulmonary	 Figure F. Systemic RV (see text).

Figure A. Transthoracic echocardiography parasternal long-axis view with a measured LVIDd of 5.38 cm.
Figure B. Transthoracic echocardiography apical 4-chamber view with RV size appearing larger (*double-headed red arrow*) than the LV based on qualitative assessment.
Figure C. Transesophageal echocardiography midesophageal bicaval view showing a secundum ASD is seen by both 2D and with the use of color Doppler with noted bidirectional flow (*red arrow*) between the LA and RA. The concern is with development of a right-to-left shunt and refractory hypoxia resulting from LV unloading and decreased LAP after LVAD activation. The defect measured ~1.3 cm.
Figure D. Transthoracic echocardiography parasternal long-axis view with moderate to severe MR (*red arrow*) with more than 50% LA area involvement due to apical tethering of normal mitral leaflet caused by LV enlargement and restricted leaflet motion.
Figure E. Computed tomography illustration of a graft (*red arrow*) within 10 mm from the sternum.
Figure F. Computed tomography illustration of a systemic RV.

section Clinical and Echocardiographic Findings Associated with LVAD Low Flow Alarms). These findings should be communicated to the implanting surgeon in real time. In addition, the cannula position could change following chest closure.

Outflow Graft. The LVAD outflow graft is anastomosed to the ascending aorta on the anterior surface along the greater curvature. The outflow graft-to-aorta anastomosis area can often be imaged by TEE, using long-axis or short-axis views of the ascending aorta at the level of the right PA. Interrogation of velocities with CW Doppler should show a baseline peak systolic flow velocity less than 2 m/sec. However, due to the underlying artificial pulse, a peak velocity greater than 2 m/sec may be seen (Figure 14). Flow acceleration and higher velocities can be seen if there is obstruction at the anastomotic site. If the obstruction is significantly proximal to the anastomotic site, the velocities may be low, with a faint Doppler signal, and have less systolic-to-diastolic (S/D) variability.[3] Of note, current recommended reference values do not take into consideration differences in pump design and outflow graft size for the newer devices. Based on a report of 216 patients with the HM3, HM-II, and HVAD, peak velocities were different for all 3 LVADs.[46] The mean peak velocities for the HM3, HM-II, and HVAD were 1.54 ± 0.458 m/sec, 1.74 ± 0.575 m/sec, and 2.07 ± 0.762 m/sec, respectively.

Right Ventricular Function. Transesophageal echocardiography provides continuous physiologic information regarding LV unloading, patient volume status, and RV function. Ideally, the IVS is positioned midline, without leftward bowing. Excessive leftward ventricular septal deviation or "suck-down" (e.g., a decrease in LV size accompanied by RV dilation and dysfunction) indicates decreased preload to the LVAD in the setting of RVF and should prompt a reduction in LVAD speed and simultaneous efforts toward restoring RV function and augmenting LV preload (Figure 15). An underfilled LV that occurs

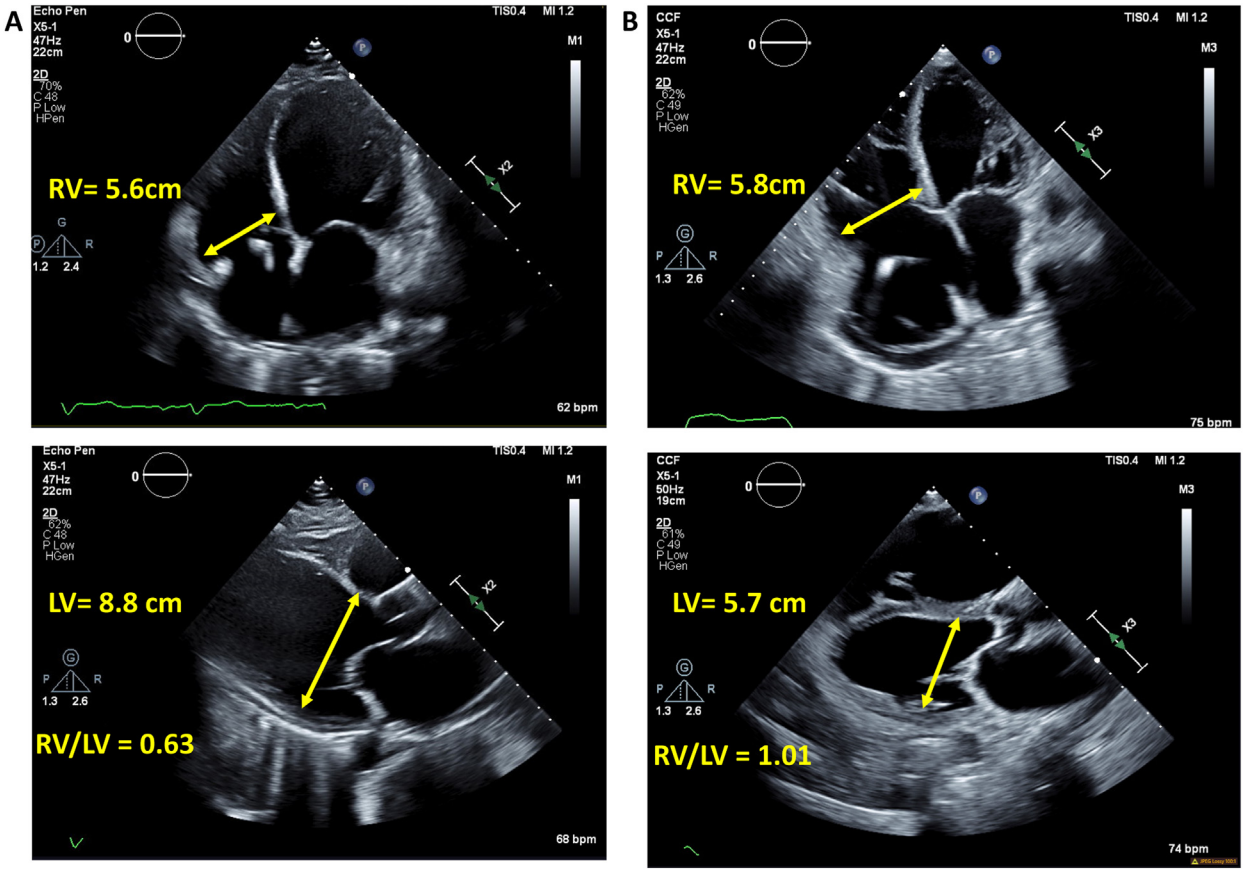


Figure 8 Right ventricular/LV size ratio defined by echocardiography. **(A)** Apical 4-chamber view (*upper panel*) and parasternal long-axis view (*lower panel*) illustration of RV/LV diameter ratio acquisition in a patient deemed at lower risk of RVF with an RV/LV size ratio of 0.63. **(B)** The RV/LV diameter (ratio 1.01) obtained using similar views in a patient deemed at high risk of RVF. Both patients had severely depressed LV and significantly depressed RV systolic function.

at relatively low pump speeds represents severe RV dysfunction and may indicate the need for biventricular support. A decrease in size of both ventricles, in contrast, may indicate significant hypovolemia.

Key Points: Intraoperative TEE Before Implantation and During LVAD Activation and Speed Optimization

- An important technological advancement of the HM3 pump is the artificial pulse, which is a cyclic change in the rotor speed every 2 seconds (30 times/min), resulting in a reduction in blood stasis and pump thrombosis.
- Echocardiographers should be familiar with the specific spectral Doppler flow patterns in the inflow cannula and outflow graft with the HM3 due to the artificial pulse.
- A comprehensive intraoperative TEE examination should be performed prior to device placement. Improved visualization of cardiac structures with TEE may enable the detection of important conditions that may have changed or were not adequately visualized during prior studies.
- The preimplantation echocardiographic focus is on LVAD cannulation sites (LV apex and aorta), exclusion of hemodynamically significant valve lesions, detection of LA, LAA, or LV masses or thrombus, detection of intracardiac shunts, and evaluation of baseline RV function using recommended views and guidelines.
- Assessment of AV opening, the relative LV and RV sizes, degree of TR, ventricular septal position, inflow cannula position, and flow velocities is recommended after initiation of LVAD support and after changes in the LVAD pump speed.
- The postimplantation TEE examination should document the impact of the new hemodynamic conditions on preexisting valvular heart disease and RV function. Establishing a new post-procedure baseline in this patient population becomes relevant for further follow-up.

PERIOPERATIVE ECHOCARDIOGRAPHY FOR TEMPORARY MCS

Intra-Aortic Balloon Pump Deployment

A detailed description of echocardiography-guided placement of the IABP has been presented in recent ASE guidelines.[37] For optimal circulatory support, when placed through the femoral artery, the position of the IABP catheter tip should be in the descending aorta, 1 to 2 cm distal to the left subclavian artery. Three-dimensional TEE

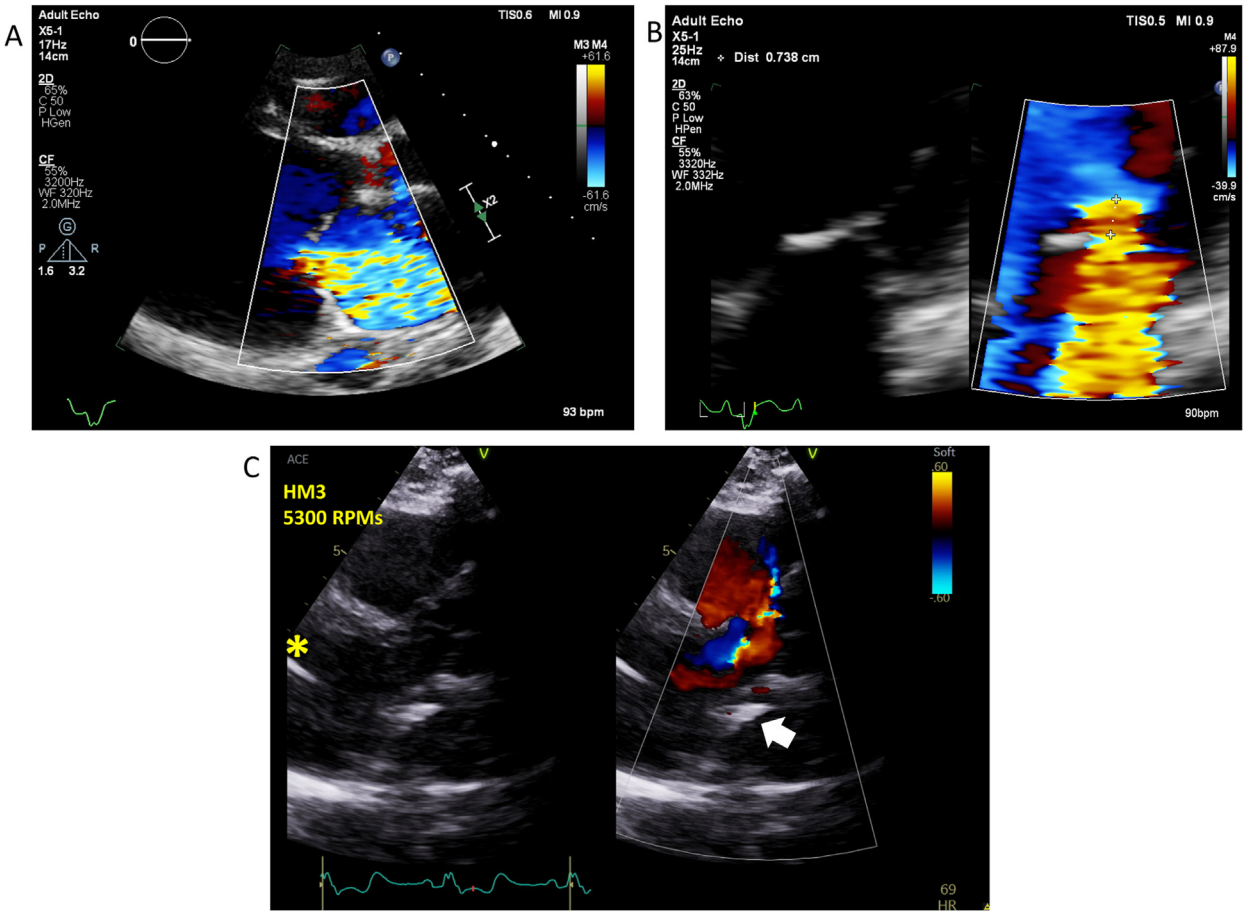


Figure 9 Pre-LVAD implantation significant MR and MV repair. Pre-HM3 severe MR. Significant MR from the parasternal long-axis view with more than 50% LA area involvement **(A)** and a flow convergence radius of 0.73 cm **(B)** is shown. Mitral regurgitation is due to apical tethering of normal mitral leaflet caused by LV enlargement and restricted leaflet motion. Parasternal long-axis view after 1 year of HM3 support at 5300 rpm (**C**; *yellow asterisk* marks the inflow cannula) and status post–MV annuloplasty ring size 27 (*white arrow*) placed at the time of LVAD implantation with only mild MR noted.

may be helpful to identify the IABP catheter tip since its position can be missed with 2D-only imaging.

Impella Deployment and Support

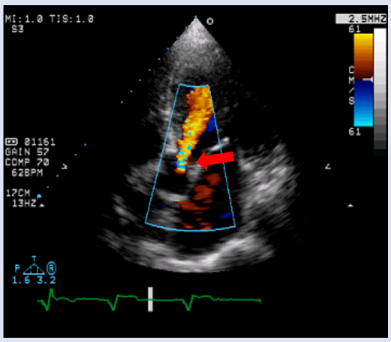
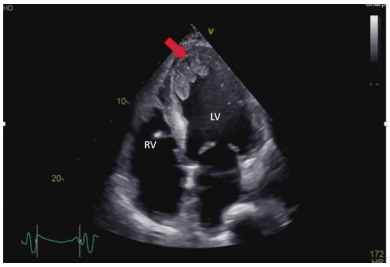
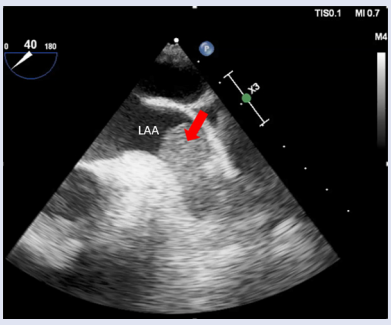
Echocardiography is invaluable during Impella device placement as it provides information regarding the position of the guidewire and the device itself in relation to neighboring structures (e.g., aortic annulus, MV apparatus, LV walls). Deployment is usually performed under a combination of fluoroscopy and echocardiography (TEE or TTE). If TEE is used during deployment, the guidewire should be visualized throughout its course in the descending aorta (if the insertion of the device is femoral), in the ascending aorta, and through the AV into the LV cavity. The guidewire should move freely inside the cavity, pointing toward the LV apex, away from the MV leaflets and the subvalvular apparatus. After confirmation of correct placement of the guidewire, the device is advanced over the wire and across the AV. The ability to identify the components of the Impella catheter with either TEE or TTE using both 2D and 3D modes is paramount to establish the correct placement of the device. The device inlet zone appears as a hypoechoic (dark) space between the cannula and a distal hyperechoic (bright) teardrop structure, which is in line with the cannula (Figures 16 and 17).

Different from the Impella 5.5, Impella CP has a flexible pigtail mounted to the distal teardrop structure. The distal pigtail helps stabilize the device and may enable redeployment without a wire if the device inflow zone migrates past the AV. Another echogenic component of the device is the motor housing neighboring the outlet, which should be positioned in the ascending aorta and can be recognized by the mosaic artifact it generates when imaged with CFD. An inadequate Impella device position is illustrated in Figure 18.

Ideal Impella positioning characteristics include the following: (1) the device is stable and directed toward the LV apex, (2) the inlet zone is free-floating (away from the MV subvalvular apparatus and the LV walls), (3) the cannula bend is situated at the aortic annulus, (4) the distance from the aortic annulus to the middle inlet point is approximately 5 cm for the Impella 5.5 and 3.5 cm for the Impella CP, and (5) the outlet is unobstructed and positioned within the ascending aorta, well above the AV.

Reversible worsening MR or AR during device positioning may result from device-related tethering of the MV or AV. However, MV or AV leaflet damage is also a possibility, related to strong suction near the device inlet or direct mechanical injury. Other complications associated with placement of the device include myocardial injury with LV wall perforation and resultant pericardial effusion and cardiac tamponade, aortic dissection, and vascular injury.[40,47]

Table 3 Red flag findings on TTE/TEE before TMCS implantation

	Findings	Example illustrations
IABP	>mild AR (see adjacent Figure A, *red arrow*) Aortic dissection Significant atheromatous disease (large, mobile plaques)	 Figure A. Moderate AR (see text).
Impella CP, 5.5	LV, LA, RV VSD ASD LV thrombus (see adjacent Figure B, *red arrow*) LA thrombus LV rupture Small LV Narrow LVOT Significant RV dysfunction Valvular abnormalities ≥moderate MS Significant myxomatous MV disease ≥moderate AR Mechanical aortic prosthetic valve Severe AS with AV area ≤0.6 cm^2 Other Aortic dissection Cardiac tamponade Significant atheromatous disease Other aortic pathology (coarctation, aneurysm) Any congenital heart disease	 Figure B. Multiple LV apical thrombi (see movie 2).
TandemHeart	LA, RV Small LA size LA and LAA thrombus (see adjacent Figure C, *red arrow*) Preexisting interatrial device Significant RV dysfunction Other Aortic dissection Any congenital heart disease	 Figure C. Left atrial appendage thrombus (see movie 3).

(*Continued*)

Table 3 (*Continued*)

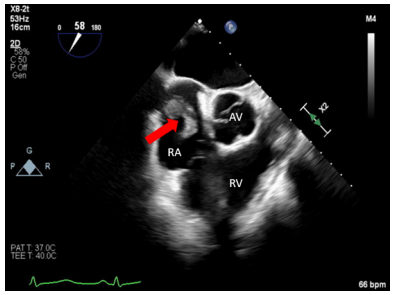
	Findings	Example illustrations
Impella RP, ProtekDuo	RA, RV, PA IVC or SVC strictures or thrombi Congenital abnormalities (interrupted IVC, absent right SVC, prominent Chiari network) IVC filters RA, RV, or PA thrombi or masses (see adjacent Figure D, *red arrow*) Valvular abnormalities Mechanical prosthetic TV Mechanical prosthetic PV ≥moderate TV or PV stenosis ≥moderate PR Other Significant uncorrected left heart disease (LV dysfunction, valvular abnormalities) Severe pulmonary hypertension	 Figure D. Mobile RA mass.

Figure A. Transthoracic echocardiography 5-chamber view illustration of AR (*red arrow*).
Figure B. Transthoracic echocardiography 4-chamber view illustration of multiple mobile LV apical thrombi (*red arrow*).
Figure C. Transesophageal echocardiography midesophageal view illustration of an LAA thrombus (*red arrow*).
Figure D. Transesophageal echocardiography midesophageal RV inflow-outflow view illustration of a mobile RA clot (*red arrow*).

TandemHeart Deployment and Support

The TandemHeart is usually placed under combined fluoroscopic and TEE guidance. Guidance of the transseptal puncture by echocardiography requires knowledge of the anatomy of the IAS and associated structures, which has been reviewed in other ASE guideline documents.[48] Placement of the transseptal inflow cannula involves identification of the fossa ovalis, placement of the guidewire transseptally into the LA and in the left superior pulmonary vein, serial dilation of the transseptal puncture, and insertion of the inflow cannula into the LA. The best position for transseptal access is through the middle of the fossa ovalis, which allows for the device cannula to be in the middle of the LA and less likely to abut the LA wall (Figure 19).[49] However, because of the multiperforated design of the cannula with 14 access points from the tip, even if the final position of the cannula is against the LA wall or even within the LAA, optimal drainage may occur.[3] Complications associated with transseptal puncture include perforation of adjacent structures, such as the coronary sinus, posterior right atrial (RA) wall, or aortic root. During support, adequate device inflow cannula positioning should be reconfirmed, especially if inadequate LV circulatory support, right-to-left shunting, and/or hypoxemia occur. Because the device delivers pressurized blood flow to the aorta increasing the LV afterload, echocardiographic monitoring should be performed to rule out blood flow stasis and thrombus formation in the aortic root and the LV, particularly when no AV opening is observed.

Centrally Cannulated LV TMCS

Cannulation is achieved generally via median sternotomy by (1) direct cannulation of the LV apex (visible by echocardiography) or cannulation of the LA directly at the level of the interatrial groove in the vicinity of the right upper pulmonary vein or through a graft sutured in the same area (which may not be visible by echocardiography)[50] and (2) ascending aorta cannulation either directly or through a graft attached to the anterior surface of the ascending aorta through which the outflow cannula is passed. Several extracorporeal centrifugal pumps can be used with these cannulation configurations (Table 1).

Transesophageal echocardiography is utilized during initiation of flow to guide removal of air that may be present in the LV. Like the position of cannulas for a durable LVAD, the inflow cannula placed in the LV apex for central TMCS can be visualized by echocardiography and should be located centrally and pointing toward the MV. Flow should be demonstrated in both the inflow and outflow cannulas by CFD. Periodic surveillance echocardiography (TTE or TEE) to monitor for development of LV and/or aortic root thrombus is needed, particularly when the level of MCS provides complete LV bypass (e.g., no AV opening demonstrated by echocardiography). In addition, causes for inability to achieve adequate LVAD flow such as hypovolemia, external compression from pericardial effusion or thrombus, or RV dysfunction can be diagnosed on a problem-focused echocardiographic exam.

Percutaneous RV TMCS Deployment and Support

Both the Impella RP and ProtekDuo cannulas are ideally placed under combined fluoroscopic and echocardiographic guidance with similar imaging goals during placement and for monitoring purposes. During placement, the distal tip of the device should be guided into the main PA (Figures 20 and 21) and not more distally into the right or left PA where it may lead to the overperfusion of one lung. Inadequate RV decompression in the presence of normal flows can be an indication of proximal migration of the distal tip of the device below the PV into the RV outflow tract (RVOT; Figure 22). In this situation the device should be advanced and repositioned under fluoroscopic or echocardiographic guidance. During support, the most common causes of low flow include (1) the presence of thrombus partially occluding the inflow or outflow cannulas, (2) hypovolemia, and (3) pericardial hematoma or effusion (tamponade). Careful

Table 4 Red flag findings on TTE/TEE before ECMO implantation

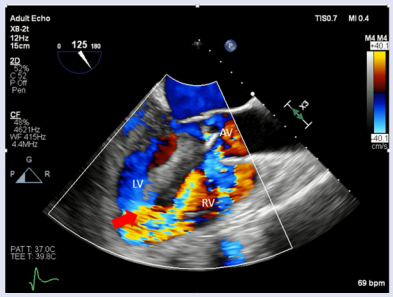
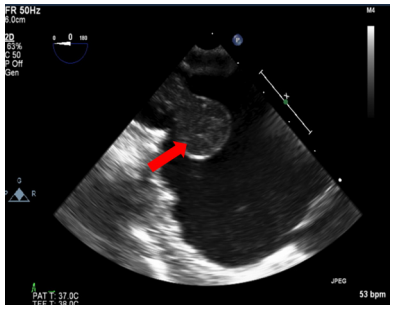
Type of ECMO	Red flag findings	Example illustrations
VA ECMO	During deployment IVC strictures or thrombi IVC filters RA clot, masses, pacemaker/defibrillator leads Atrial septal aneurysm ASD or VSD (see adjacent Figure A, *red arrow*) Prominent Chiari network Aortic dissection Significant atheromatous disease ≥moderate AR During support LA, LV dilation Absence of AV opening Significant MR Spontaneous echo contrast or clot in LV apex and aortic root	 Figure A. Post–myocardial infarction VSD (see text).
VV ECMO	During deployment IVC or SVC strictures or thrombi (see adjacent Figure B, *red arrow*) Congenital abnormalities (interrupted IVC, absent right SVC, prominent Chiari network) IVC filters RA, RV, or PA thrombi or masses Prominent Chiari network Atrial septal aneurysm ASD Severe RV or LV dysfunction	 Figure B. Thrombus obstructing the IVC.

Figure A. Transesophageal echocardiography midesophageal long-axis view illustrating a complex mid-to-distal IVS rupture with predominant left-to-right shunting (*red arrow*) noted on peripheral VA ECMO despite venting with an IABP.
Figure B. Transesophageal echocardiography modified bicaval view showing a large clot (*red arrow*) at the IVC/RA junction.

examination in multiple views should be performed to rule out the presence of clot or blood in the pericardium as these effusions can be loculated.

Centrally Cannulated RV TMCS

Central RVAD support can be accomplished by (1) RA cannulation either by a surgical approach or percutaneously by femoral venous cannulation and (2) PA cannulation either by open direct cannulation or through a surgically constructed graft attached to the main PA through which the RVAD outflow cannula is passed. Central cannulation can be achieved either through direct sternotomy or through left thoracotomy.[51,52]

The RVAD inflow cannula is placed anteriorly at the level of the RA appendage. If the RA cannula is placed through percutaneous femoral venous cannulation, the presence of the wire should be confirmed advancing from the IVC into the RA and the cannula should be observed advancing over the wire in the RA. Very rarely the RVAD inflow cannula may be surgically placed in the RV. The RVAD outflow cannula is typically implanted at the level of the main PA. The cannula should not abut the PA walls and should not be preferentially directed toward either the left or right PA (Figure 23).

Peripheral ECMO Deployment and Support

Peripheral ECMO cannulation may be performed under fluoroscopic or echocardiographic guidance or a combination of both. Emergent bedside cannulation may preclude fluoroscopic or echocardiographic guidance. The advantage of echocardiography (TTE or TEE) is that beyond assessing the position of the cannula, it provides immediate feedback on the degree of ventricular and/or atrial unloading.[53-55] Providing useful cannula position feedback requires knowledge of the configuration of the deployed ECMO. During cannulation, echocardiography is most useful during peripherally deployed ECMO (Figure 24), as it can confirm the position of the guidewires and, after cannulation, the final position of the cannulas. For the drainage cannula, the guidewire should be seen advancing through the IVC or SVC into the RA. The echocardiographer should confirm that the wire does not advance into the RV through the TV. For the return cannula, a second guidewire should be seen in the RA (VV ECMO) or in the descending aorta (VA ECMO). Wire positions should be reconfirmed after the initial cannulation and again after deployment of the soft tissue dilator and advancement of the sheath. In the final correct position (1) the VA ECMO drainage cannula tip should be in the mid-RA cavity away from the RA walls, IAS, and TV, and (2) the VV ECMO drainage cannula tip should be just below

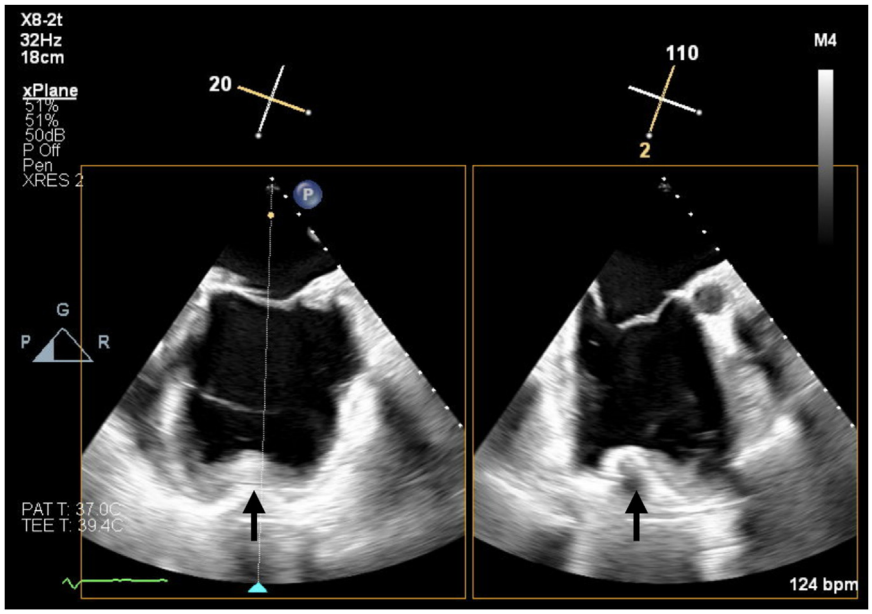


Figure 10 Transesophageal echocardiography illustration of intraoperative LV apex identification. The indentation (*black arrow*) made by the surgeon's finger can be visualized in 2 simultaneous planes of the LV.

the IVC-RA junction, in the subdiaphragmatic IVC. The VV ECMO return cannula (placed via a femoral vein or the right internal jugular [IJ] vein) should be similarly guided to the superior RA cavity. The VV ECMO drainage and return cannulas should not be in close proximity to each other as this may lead to recirculation and ineffective support.[56] Recirculation occurs when oxygenated returning blood is taken up by the drainage cannula instead of being supplied to the RV. Recirculation is rarely seen with a separation distance ≥8 cm between the cannula tips.[57]

The placement of the dual lumen bicaval cannula for VV ECMO (Avalon Elite, Getinge; and Crescent, Medtronic) necessitates echocardiography for visualization of the correct placement of the different components of the cannulas. The cannula is usually placed through the right IJ vein, although other sites of cannulation have been described (e.g., left IJ vein, left subclavian vein).[58] During TEE-guided cannulation, a bicaval view is commonly used to visualize the guidewire entering the SVC, RA, and IVC (Figure 25). Looping of the guidewire in the RA and RV should be ruled out, and visualization of the guidewire should be continued during advancement of serial dilators and the cannula.[58] In its final correct position, the cannula tip should be below the IVC-RA junction, in the subdiaphragmatic IVC, and the return port should be in the middle RA oriented toward the TV to facilitate blood flow toward the TV and the RV. Imaging the dual lumen cannula by TTE or TEE is even more critical because there may be greater propensity for the device to inadvertently cross an undiagnosed ASD, PFO, or the TV annulus or to perforate the RA.

Initiation of VA ECMO support and injection of pressurized blood return in the ascending aorta or descending aorta may increase the afterload of the LV. In the context of poor ventricular function, elevation in LV afterload can result in progressive LV distension, pulmonary congestion and edema, LV blood stasis and thrombus formation, myocardial ischemia, and delay in myocardial recovery. Initiation of LV venting, especially if implemented early, can result in a more successful weaning from VA ECMO support and reduction in short-term mortality.[59] Left ventricular venting may be accomplished by atrial septostomy as well as percutaneous (discussed below) or direct surgical cannulation of the LA, LV, or PA.[60] The more common strategies of LV unloading include the IABP and the percutaneously placed Impella catheter,[59] although the choice of LV venting may be dictated by the type of MCS already in place at the time of VA ECMO deployment, configuration of VA ECMO support (peripheral vs central), and patient-specific factors. Specifically, the combination of Impella and VA ECMO support (ECPELLA configuration)[61] has resulted in improved outcomes.[62] Echocardiographic views considerations and a proposed workflow before, during, and after percutaneous LV and RV TMCS can be found in Appendices Tables 2 and 3.

Key Points: Perioperative Echocardiography for TMCS

- Echocardiography during deployment and support of TMCS should confirm the correct placement of the cannulas.
- As devices vary depending on the ventricle supported, type of cannulation (percutaneous versus central), and cannulation configuration, device-specific echocardiographic guidance should be considered and are provided in Appendices Tables 2 and 3.

ROLE OF ECHOCARDIOGRAPHY (TTE OR TEE) AFTER LVAD IMPLANTATION

The starting point for any LVAD echocardiographic examination remains a comprehensive HF TTE exam, which is performed at the pump's baseline speed setting and includes LVAD-specific views and Doppler flow assessments in addition to all the elements of preoperative TTE.[3] We continue to advocate 3 subcategories of LVAD echocardiographic protocol indications, as defined in the 2015 Guideline,[3] to reflect real-world clinical management in

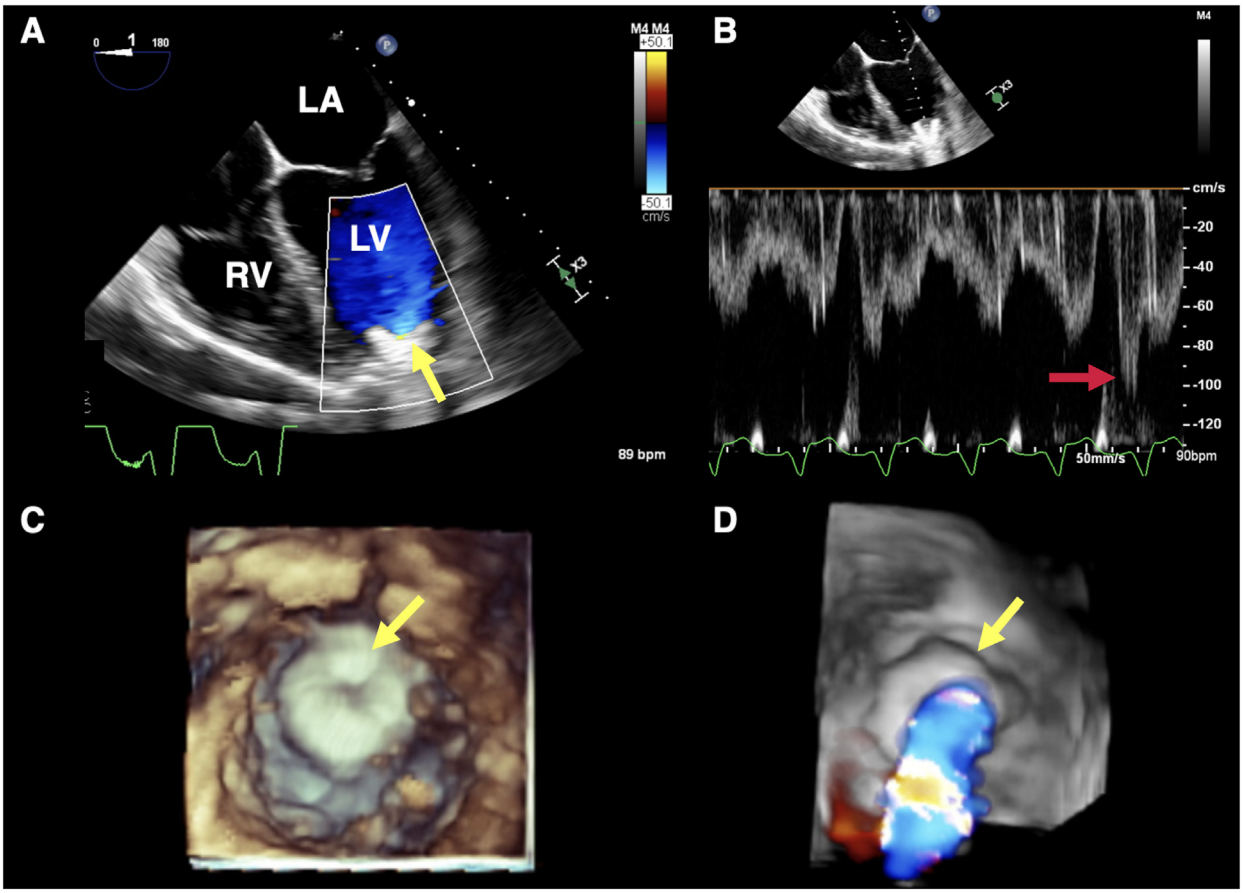


Figure 11 Transesophageal echocardiography HM3 inflow cannula position and flow assessment. HeartMate 3 inflow cannula assessed by 2D echocardiography with CFD in the midesophageal 4-chamber view showing **(A)** normal apical inflow cannula position (*yellow arrow*) directed toward the MV, **(B)** PW Doppler assessment of the inflow cannula illustrating the presence of the artificial pulse feature (*red arrow*) of the HM3 device (also see Figure 12), and **(C and D)** 3D en face view showing the centered cannula (*yellow arrow*) free of interaction with the LV endocardium.

patients supported by the HM3: (1) LVAD surveillance echocardiography, with or without LVAD optimization echocardiography, (2) LVAD problem-focused echocardiography, with or without an LVAD speed change protocol, and (3) LVAD recovery echocardiography.

Clinical Data Acquisition Standards and Blood Pressure Assessment on LVAD Support

As stated in the 2015 Guideline, before initiating any LVAD echocardiographic exam, sonographers should always annotate the LVAD type and baseline LVAD speeds in units of rpm on the imaging screen in addition to the standard patient demographic data.[3] The patient's blood pressure (BP) remains an important parameter, and although BP assessment in patients with LVADs can be challenging, recent observations suggest that successful automated cuff measures of BP in patients supported by the HM3 are most valid for estimation of the mean arterial pressure.[63] For practical purposes, we continue to recommend that if the patient has a pulse (e.g., the AV is opening with every beat), the opening Doppler pressure is the same as the systolic BP. If the patient does not have a pulse (e.g., the AV is not opening on imaging with every beat and/or very partial and infrequent opening is seen), the opening Doppler pressure is considered to be the mean arterial BP.

Key Points: BP Assessment on LVAD Support

- Although BP readings remain challenging to obtain in LVAD patients, including those supported by the HM3, this variable remains important, as it significantly influences observed echocardiographic findings and their interpretation.
- The automatic cuff BP reading should be used and recorded when a BP is detected.
- In the absence of an automatic BP reading, BP measurements continue to require audible Doppler interrogation by an appropriately trained individual before the echocardiographic exam to define the opening Doppler pressure.
- In the absence of detected automatic BP cuff reading and in the absence of a palpable pulse, the recorded opening Doppler pressure is interpreted as the mean BP.
- A mean arterial BP between 65 and 85 mm Hg remains the recommended goal.

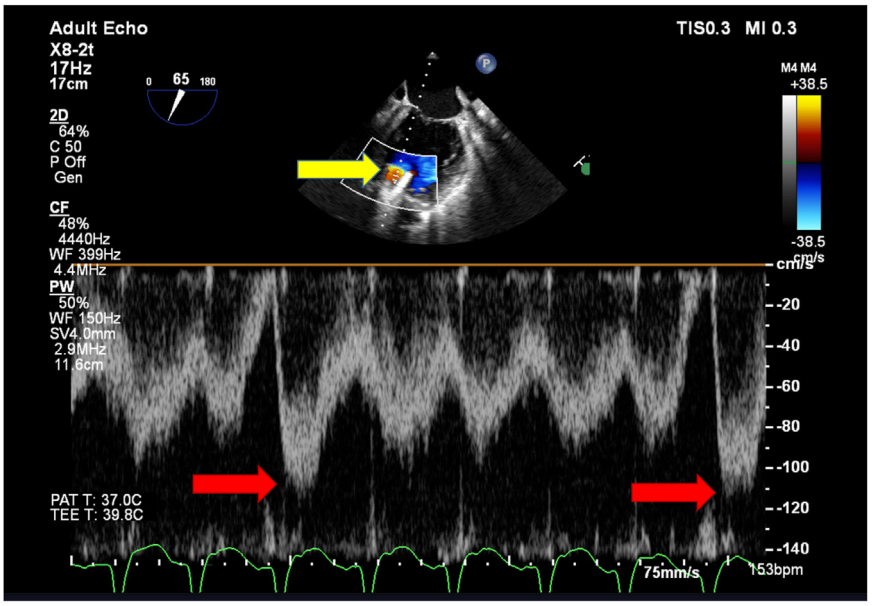


Figure 12 HeartMate 3 inflow cannula flow characteristics. Assessment of HM3 inflow cannula flow using TEE and PW Doppler with the *yellow arrow* indicating the site of the sample volume. The intermittent increase in the peak velocity is attributed to the artificial pulse (*red arrows*) as described in the text.

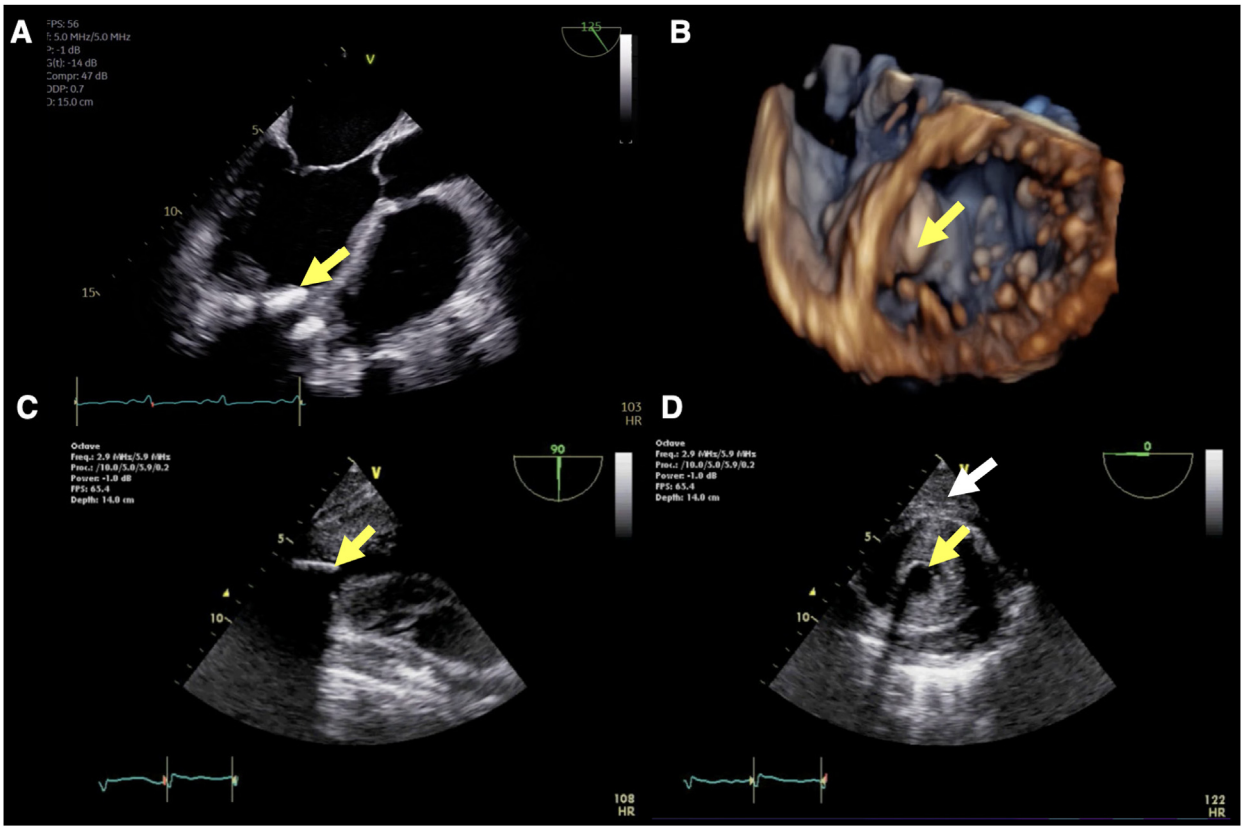


Figure 13 Transesophageal echocardiography–detected inflow cannula malposition. **(A)** Left ventricular assist device inflow cannula seen angulated toward the IVS in the midesophageal long-axis view. **(B)** Same cannula seen abutting the IVS in the 3D en face view. **(C)** Severely underfilled LV seen in a different patient in the transgastric long-axis view, with the LVAD inflow cannula abutting the wall. **(D)** Same cannula seen in the transgastric short-axis view. In addition, clot is present in the pericardium around the LV (*white arrow*). *Yellow arrows* indicate the LVAD inflow cannula.

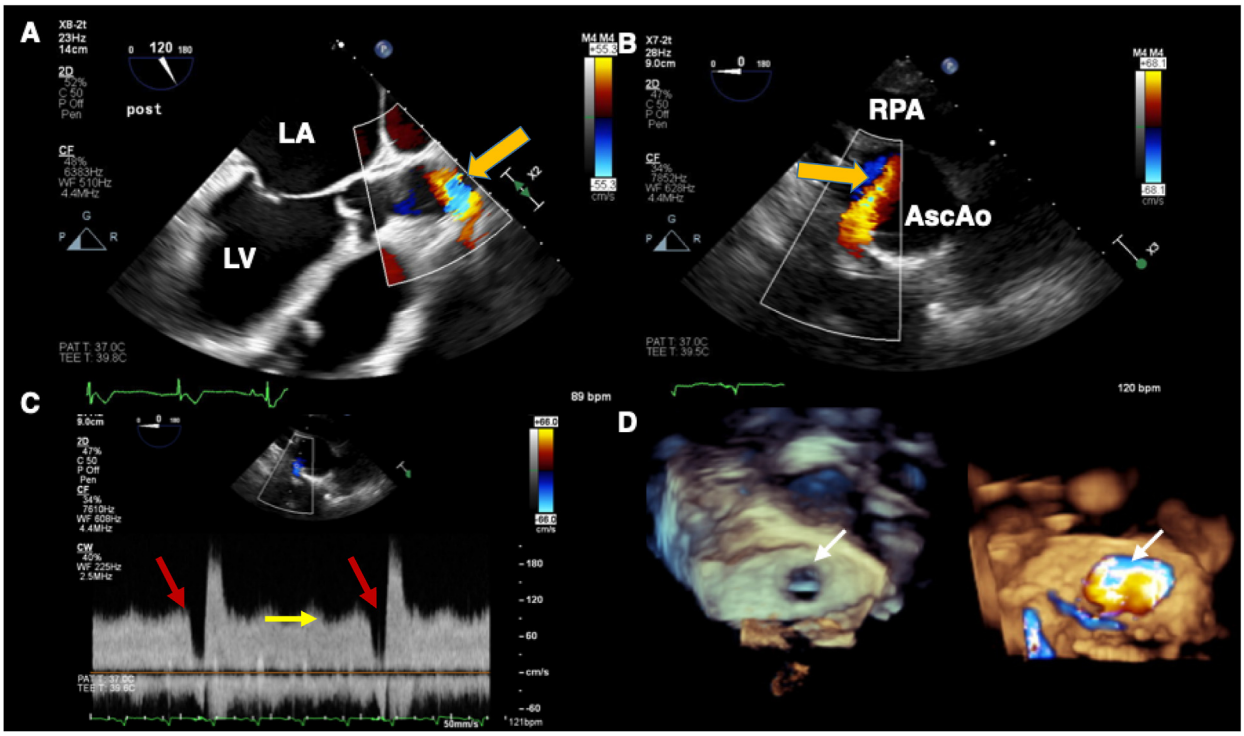


Figure 14 Transesophageal echocardiography HM3 outflow graft anastomosis and flow assessment. Left ventricular assist device outflow graft assessed by 2D echocardiography with CFD in long-axis **(A)** and short-axis **(B)** views with illustration of blood flow propelled into the ascending aorta at the outflow graft anastomosis site (*orange arrows*). **(C)** Continuous-wave Doppler illustration of the artificial pulse feature of the HM3 device occurring every 2 seconds with illustration of the rapid decrement then rapid increment in outflow graft velocity (~210 cm/sec; *red arrows*) compared to baseline CF (*yellow arrow* corresponding to a velocity of 90 cm/sec). **(D)** Three-dimensional en face views showing the suture line (*white arrows*) of the outflow graft in the AscAo with CFD (*right image*) and without (*left image*). *AscAo*, Ascending aorta; *RPA*, right PA.

Left Ventricular Size and Systolic Function on LVAD Support

Methods for determining LV size and systolic function by using linear and volumetric approaches in HF patients are established.[64] We refer readers to the 2015 Guideline document that defines LV size and systolic function determination in patients supported by LVADs[3] and the importance of following LV size over time. These recommendations apply equally to patients supported by the HM3. Strong consideration should be given to the use of ultrasound-enhancing agents (UEAs) when endocardial definition is insufficient for accurate LVIDd measurement. The safety and feasibility of UEA use for the evaluation of patients with LVADs including the HM3 has been demonstrated.[65,66]

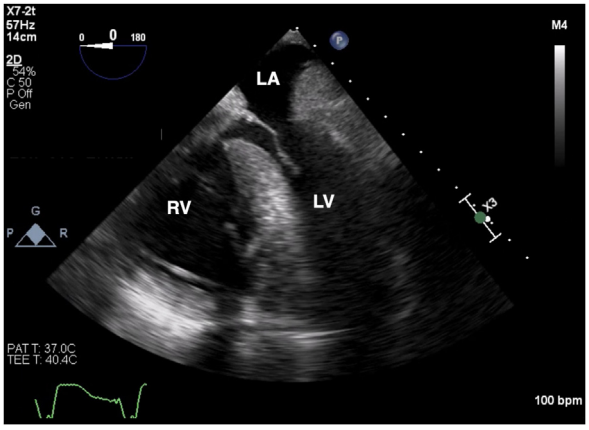


Figure 15 Post–LVAD implantation suction event demonstrated by TEE. Echocardiographic changes seen with the midesophageal view illustrating a suction event consisting of a severely underfilled LV with shifting of the IVS toward the left and associated with dilation of the RV. The event was accompanied by severe RV dysfunction and hypotension.

Key Points: LV Size and Function on LVAD Support

- After CF LVAD activation, the LVIDd remains the most reproducible measure of LV unloading that can be tracked over time and/or at different pump speeds.
- After LVAD implantation, measurement of LV volumes and LVEF can be technically challenging.
- UEA use is safe and recommended when endocardial definition is insufficient for accurate LV size and/or systolic function assessment in patients supported by LVADs.

Left Ventricular Diastolic Function After LVAD Implantation

Standard LV diastolic parameters reflect the degree of LV unloading provided by the LVAD.

There have been 2 reports that validate the accuracy of echocardiography to detect elevated LAP and RA pressure (RAP) in patients supported by LVADs. Estep *et al.*[67] showed that Doppler echocardiography accurately estimated intracardiac hemodynamics in patients supported with the HM-II. Frea *et al.*[68] further validated the use of echocardiography in patients supported by the HVAD and demonstrated that the estimated LAP and RAP significantly correlated with invasively determined pulmonary capillary wedge pressure and RAP ($r = 0.889$, $P < .001$ and $r = 0.839$, $P < .001$, respectively). Moreover, this study demonstrated that optimal unloading, defined as a normal estimated LAP and RAP assessed noninvasively, is associated with a lower risk of adverse cardiac events (composite of HF hospitalization, death, or urgent transplantation) at follow-up when compared with other nonoptimal profiles (odds ratio, 0.2; 95% CI, 0.1-1.0; $P < .05$). In contrast with the 2015 Guideline,[3] we recommend assessing diastolic function in patients supported by LVADs in accord with the existing ASE guidelines for the evaluation of LV diastolic function.[69] However, validation studies in patients supported by the HM3 are lacking.

Key Points: LV Diastolic Function on LVAD Support

- Doppler echocardiographic estimates of LAPs and RAPs accurately reflect LV and RV filing pressures while on LVAD support.
- Patients with suboptimal ventricular filling pressures on LVAD support are at risk for adverse cardiac events related to persistent HF.
- Echocardiographic parameters used to help define elevated LAPs while on LVAD support include the mitral E/A ratio, LA volume index, E/e' ratio, and the estimated systolic PA pressure and, importantly, the RAP estimate.

Left Ventricular Apical Inflow Cannula Assessment

As defined in the 2015 Guideline[3] and above (see "Transesophageal Echocardiography During LVAD Activation and Speed Optimization"), it remains important to define the position of the inflow cannula and associated Doppler profile. The TTE parasternal long-axis, short-axis, and apical views are helpful to define the HM3 inflow cannula position and its direction and freedom from adjacent structures (Figure 26). Inflow cannula malposition in patients with the HM3 may influence the degree of LV unloading and freedom from HF and has been shown to be a risk factor for stroke (Figure 27).[70] The peak HM3 inflow cannula velocity is typically less than 1.0 m/sec with the artificial pulse creating a intermitting peak velocity up to 1.2 m/sec.

Right Ventricular Size and Systolic Function After LVAD Implantation

As stated in the 2015 Guideline,[3] many of the standard measures of RV size and systolic function should be reported in LVAD patients. Current observations highlight the need to continually assess for late RVF (Figure 28) beyond 30 days after implantation and to follow patients beyond the first year after LVAD placement for the development of late RVF.[14,16]

Valvular Assessment After LVAD Implantation

Aortic Valve. Evaluating and reporting the degree of AV opening and AR remains important as defined and recommended in the 2015 Guideline.[3] In contrast to older guidelines that recommended that the LVAD speed should be set low enough to allow at least intermittent AV opening, it is important to highlight that this is a secondary goal and remission of HF symptoms and signs remains the priority. In HM3 recipients, HF-related events were among the most common causes of rehospitalization after LVAD placement and the first rehospitalization attributed to underlying HF compared to other causes was associated with reduced survival.[71] Higher levels of pump speed support may be required to adequately unload the LV to improve HF symptoms, albeit potentially at the expense of normal and/or intermittent AV opening.

The presence of the artificial pulse in HM3 devices does not change our recommendation to define the AV opening status as persistently closed (no opening noted), intermittent opening, or opening noted with each cardiac beat. In fact, the artificial pulse typically does not equate to intermittent AV opening visualized by echocardiography (Figure 29).

As previously defined, the complications of persistent AV closure include aortic root thrombus and LVAD-associated AR.[3] Known risk factors for the development of AR while on LVAD support, in addition to a closed AV, include advanced age, lower body surface area, systemic hypertension, large aortic root diameter, longer duration of LVAD support, and female sex.[72,73] Based on a recent MOMENTUM 3 trial analysis, at 2 years of LVAD support, freedom from moderate or severe de novo AR was greater in the HM3 (92%) than in the HM-II (82%; hazard ratio, 0.45; 95% CI, 0.27-0.75, $P < .01$). The occurrence of significant de novo AR with the HM3 pump was not associated with a worse outcome at 2 years of follow-up.[73] An example of significant AR in a patient supported by the HM3 is shown in Supplemental Figure 4.

To improve the accuracy of AR assessment with a CF LVAD, novel echocardiographic parameters have been proposed: (1) peak S/D velocity ratio of the outflow cannula, a metric that is inversely proportional to AR severity, and (2) diastolic acceleration of outflow cannula flow, a metric that is directly proportional to AR severity (Figure 30). Moderate or greater AR, correlating with a regurgitant fraction of ≥30%, was defined as an S/D ratio of <5.0 or a diastolic acceleration of >49.0 cm/sec^2.[74] Interestingly, these parameters better captured AR under CF LVAD conditions as they are specifically based on the close interplay that exists between the variations in flow through the outflow cannula and loading conditions.

These innovative parameters, albeit based on single-center observations, showed better correlation with LV filling pressures and AR fraction than traditional criteria.[74,75] In addition, AR severity based on these novel Doppler echocardiographic measurements is associated with a higher incidence of death or HF readmissions compared to those without significant AR.[76] However, validation studies are lacking.

Regarding medical and surgical treatment for patients with significant AR while on LVAD support we refer readers to the review by Bouabdallaoui and colleagues.[72] Although increasing the LVAD pump speed, ideally guided by invasive hemodynamics and echocardiography, may ameliorate symptoms in some patients, higher speeds tend to increase AR severity and can further perpetuate aortic cusp degeneration and hemodynamic impairment. Since the 2015

Guideline,[3] the use of transcatheter AV replacement for treatment of LVAD patients with symptomatic AR (Supplemental Figure 4) has evolved.[77,78] Although recent reports utilizing self-expanding transcatheter heart valves to treat LVAD-associated AR are encouraging regarding efficacy, the data are still limited to several case reports. Furthermore, adequate anchoring of the device remains a concern when calcific AS is absent.

Mitral Valve. Significant MR on LVAD support (Figure 31) is a surrogate of partial LV unloading and is potentially reversible if due to uncontrolled hypertension, a relatively low pump speed setting, inflow cannula malposition, outflow cannula graft obstruction, and/or pump rotor malfunction. Echocardiography is the first-line test to confirm the severity of MR according to published guidelines[24] and can help identify the underlying cause(s). As defined below, optimization echocardiography is useful to help detect the pump speed setting associated with greatest reduction in MR (Figure 31). There is a paucity of data regarding the safety and efficacy of surgical and percutaneous MV interventions to treat patients with significant MR on CF-LVAD support.

Key Points: Apical Inflow Cannula, RV Size and Function, and Valve Assessment on LVAD Support

- HM3 inflow and outflow cannula velocities include an intermittent peak systolic velocity variation, attributed to the artificial pulse that is due to an automatic ramp-down then ramp-up every 2 seconds, and should not be mistaken for intermittent obstruction.
- The peak HM3 inflow cannula velocity is typically less than 1.0 m/sec, with the artificial pulse creating a peak intermitting peak velocity up to 1.2 m/sec.
- Although freedom from moderate or severe de novo AR is greater in patients with the HM3 than with the HM-II, acquiring significant AR on LVAD support is possible.
- Novel indices based on the outflow cannula velocity profile may be used to detect moderate or greater AR while on LVAD support.
- Persistent significant post-LVAD implantation MR despite device and medical optimization can occur and has been associated with increased morbidity.

Echocardiography With Speed Changes and Safety Concerns

Speed change testing typically occurs in the setting of either an optimization protocol or a problem-focused (ramp) exam. We continue to advocate the use of a structured ordering template to assist with understanding up-front safety concerns and the following: (1) which speeds should be tested as ordered by the MCS team, (2) which criteria define the "optimal" LVAD speed for a particular patient, (3) what LVAD speed should be set at the conclusion (the initial baseline or the optimized speed), and (4) what the reasons are to stop a speed-change (ramp) test. Table 5 includes echocardiogram types and a sample LVAD and TMCS exam checklist, as the concepts provided here apply to patients supported by TMCS devices as well. Regardless of the indication(s), the LVAD and TMCS echocardiographic examination begins with all the elements of a standard surveillance exam performed at the baseline pump speed setting. After this initial portion of the exam, the number of different speeds required and the incremental speed changes needed may vary, depending on the suspected problem and the response to a speed change observed in real time. Accordingly, the speed change component of a problem-focused echocardiographic exam, as previously stated,[3] frequently requires the immediate availability of MCS team members and/or trained echocardiographic medical staff for interpreting responses to device speed changes and recognizing safety end points for the exam.

Advanced HF centers use echocardiography to help define the ideal pump speed setting for patients supported by the HM3.[79] The HM3 speed range is 3,000 to 9,000 rpm (typical clinical operating range, 4,800-5,600 rpm). The HM3 speed is typically changed in 100 rpm increments.[79,80] As defined in the 2015 Guideline,[3] to provide a margin of safety, implantation centers continue to define the optimal LVAD speed as being just below the maximum speed associated with optimal LV unloading (typically at least 200 to 400 rpm below the maximum speed for the HM-II, at least 40 rpm below the maximum speed for the HVAD, and 100 rpm below the maximum speed for the HM3). A list of basic parameters that should be assessed on a ramp/speed optimization study is included in Appendix Table 4.

Key Points: Echocardiography With Speed Change Considerations

- All HM3 echocardiography examinations should begin with the elements of a standard surveillance echocardiographic exam, performed at the baseline pump speed setting.
- The HM3 speed range is 3,000 to 9,000 rpm, with a typical clinical operating range between 4,800 and 5,600 rpm.
- The HM3 speed is typically changed in 100 rpm increments.
- We advocate use of a structured ordering template for HM3 recipients as defined in Table 5 to guide image acquisition as a surveillance (no speed change planned) tool, for problem solving at baseline speed only, or at baseline plus other speed settings, or for a myocardial recovery exam.

LEFT VENTRICULAR ASSIST DEVICE PARAMETERS AND HM3 ALARM TYPES

To acquire the appropriate echocardiographic information, sonographers and echocardiographers must have some familiarity with the different HM3 alarm types and the LVAD controller parameters (Supplemental Figure 5). Specific echocardiographic findings associated with low-flow alarm events, among the most common type of LVAD alarms, are listed in the "key points" section following the LVAD parameters discussion. High-flow alarms are less common and are typically due to systemic vasodilation, severe AR, or rotor thrombus.

Pump speed for the HM3, like the HM-II and HVAD, denotes the rpm of the impeller. The HM3 speed typical clinical operating range is 4,800 to 5,600 rpm. In contrast to the concern for the HM-II operating at lower pump speeds (e.g., <9,000 rpm), the HM3 is associated with a significantly lower incidence of pump thrombosis at lower pump speeds (<1.5%).[2] At higher pump speeds, suction events could occur for all 3 devices.

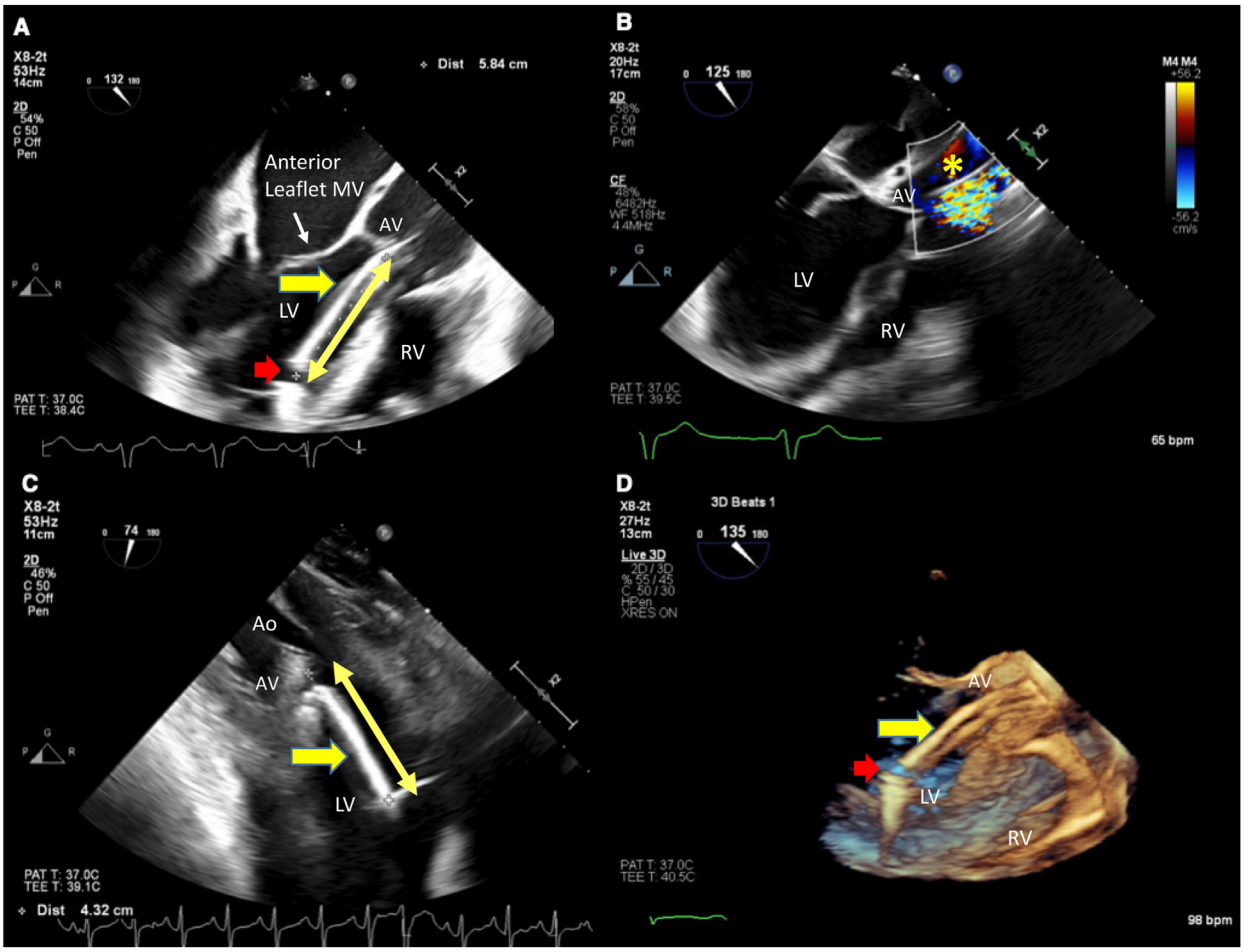


Figure 16 Transesophageal echocardiography Impella 5.5 assessment. **(A)** Midesophageal long-axis view showing the device (*single yellow arrow*) adequately placed, the bend of the cannula positioned at the AV level, and the distance between the aortic annulus and the mid-inlet portion measured at 5.8 cm (*double-headed yellow arrow*). The *red arrow* defines the blood inlet area. **(B)** Mosaic artifact (*yellow asterisk*) generated by the rotor neighboring the outlet seen by CFD in the midesophageal LAX view. **(C)** Transgastric LAX view can also be used to visualize the positioning the device (*single yellow arrow*), with the distance from the aortic annulus measured at 4.32 cm (*double-headed yellow arrow*). Different patient examination compared to *panel A*. **(D)** Three-dimensional visualization of the device in a midesophageal LAX view (*single yellow arrow*). The *red arrow* shows the blood inlet area. Three-dimensional echocardiography can provide additional information regarding the relationship of the device with the neighboring structures. *Ao*, Ascending aorta; *LAX*, long axis.

Pump power for all 3 devices is a direct measurement of pump motor voltage and current. Changes in pump speed, flow, or physiological demand can affect pump power. For the HM3, like the other devices, it is measured continuously and displayed on the controller panel as an average over time in Watts (a typical value is <10 W). Increased power may signal thrombus deposits inside the pump or AR.

Flow (L/min) for the HM3, like the other devices, is an estimated value that is directly related to the set speed and power. For the HM3, if the flow estimate falls below 2.5 L/min, the HM3 system controller will alarm "low flow." It remains practical to classify alarms, in general, as either low flow or high flow/high power. In patients supported by the HM3, low-flow alarms compared to high-flow alarms are more common in clinical practice. Low-flow alarms can be caused by cardiac tamponade, RVF, hypovolemia, inflow cannula obstruction, outflow graft obstruction (twist, kinking, outflow cannula intraluminal thrombus, or extraluminal compression), malignant hypertension, and/or arrhythmias. High-flow/high-power alarms can be caused by pump thrombosis (significantly more common with the HM-II and HVAD than with the HM3), systemic arterial vasodilation, significant AR, and/or recovery of native LV function.

Pulsatility index (PI) for the HM3, like the other devices, is a derived value calculated from the highest-to-lowest power readings over a range, divided by the average power over that range. The HM3 LVAD PI range is 1 to 10. Under otherwise stable conditions, a significant drop in the PI value may indicate a decrease in circulating blood volume. A significant increase in PI may indicate elevated BP in patients supported by the HM3.

Pulsatility index events detected with HM3 use are defined similarly to the HM-II. The HM3 employs PI detection algorithms to recognize and avert LV collapse. If a PI event is detected, the pump speed will automatically reduce to the low set speed limit and then gradually ramp back up to the fixed speed. These are typically inaudible alarms.

It remains important to place pump parameter deviations and identified alarms in clinical context. Low-flow alarms for the HM3 are defined and displayed similarly to the HM-II. For the HVAD,

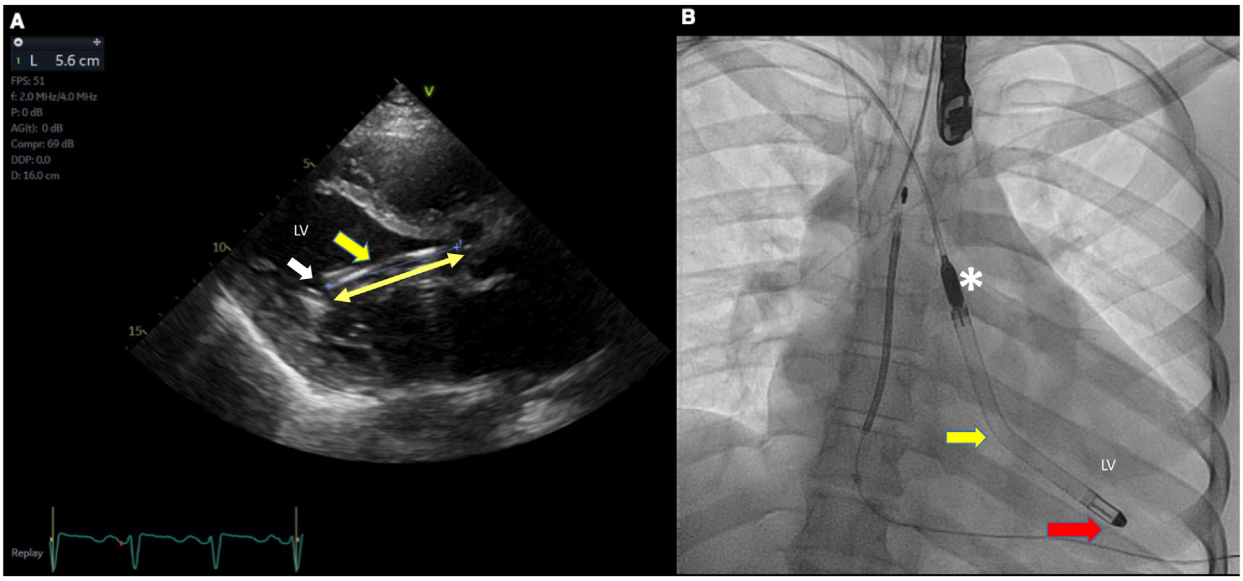


Figure 17 Transthoracic echocardiography Impella 5.5 assessment. **(A)** Transthoracic echocardiography in the parasternal long-axis view with visualization of the device (*single yellow arrow*) and a measured distance of 5.6 cm (*double-headed yellow arrow*). The *white arrow* defines the blood inlet area. **(B)** Fluoroscopy using the anteroposterior view. The *single yellow arrow* shows the device in the LV. The *white asterisk* marks the motor housing containing the microaxial rotor. Blood from the inlet (*red arrow*) located in the LV is propelled into the ascending aorta through the outlet located just below the motor housing.

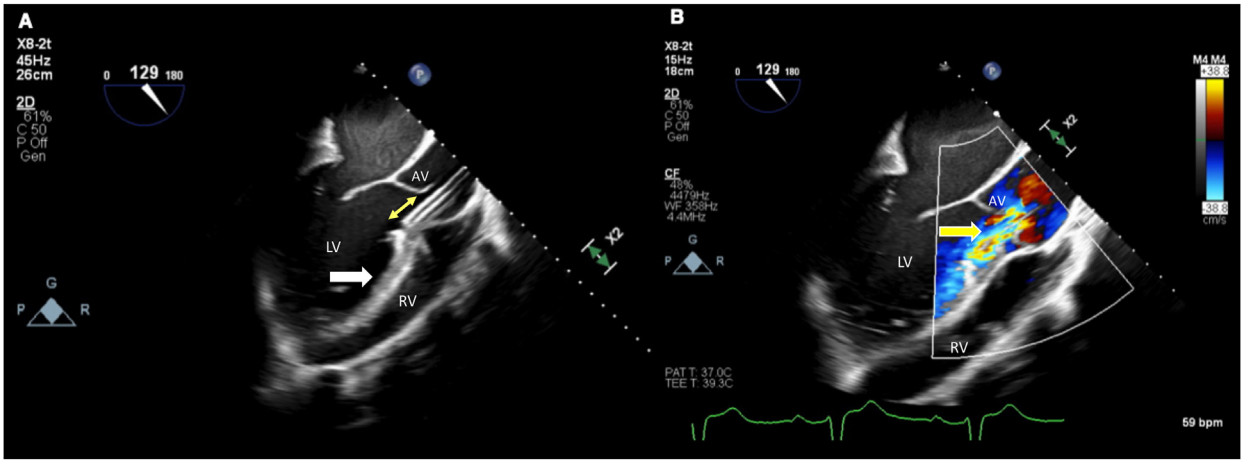


Figure 18 Transesophageal echocardiography visualization of Impella device malposition. **(A)** Midesophageal long-axis view in a patient supported by an Impella CP and VA ECMO (not illustrated). The device position is too shallow (*double-headed yellow arrow*), contributing to ineffective LV unloading with associated persistent dilation of left heart chambers, including persistent bowing of the LV septum into the RV (*white arrow*) and persistent pulmonary edema. **(B)** Significant AR (*single yellow arrow*) seen by CFD contributes to the ineffective LV unloading.

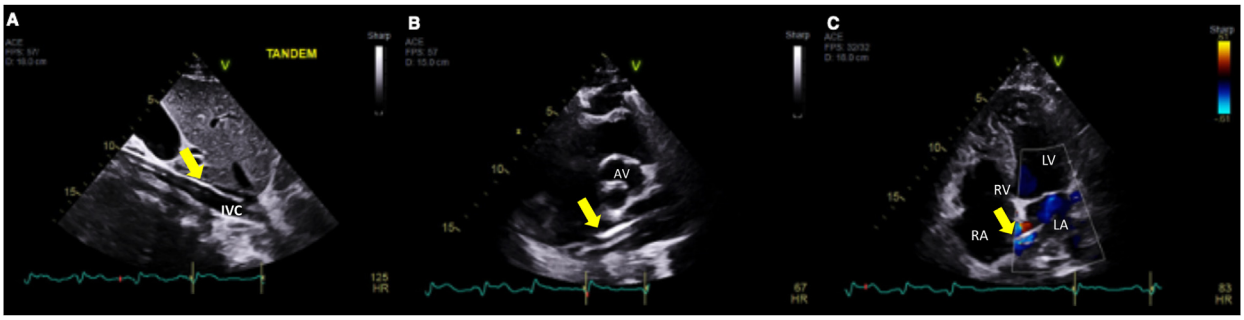


Figure 19 Transthoracic echocardiography TandemHeart assessment. **(A)** Drainage cannula (*yellow arrow*) is seen entering the RA via the IVC. **(B)** Parasternal short-axis and **(C)** 4-chamber apical view showing the Tandem cannula (*yellow arrow*) crossing the IAS from the RA into the LA.

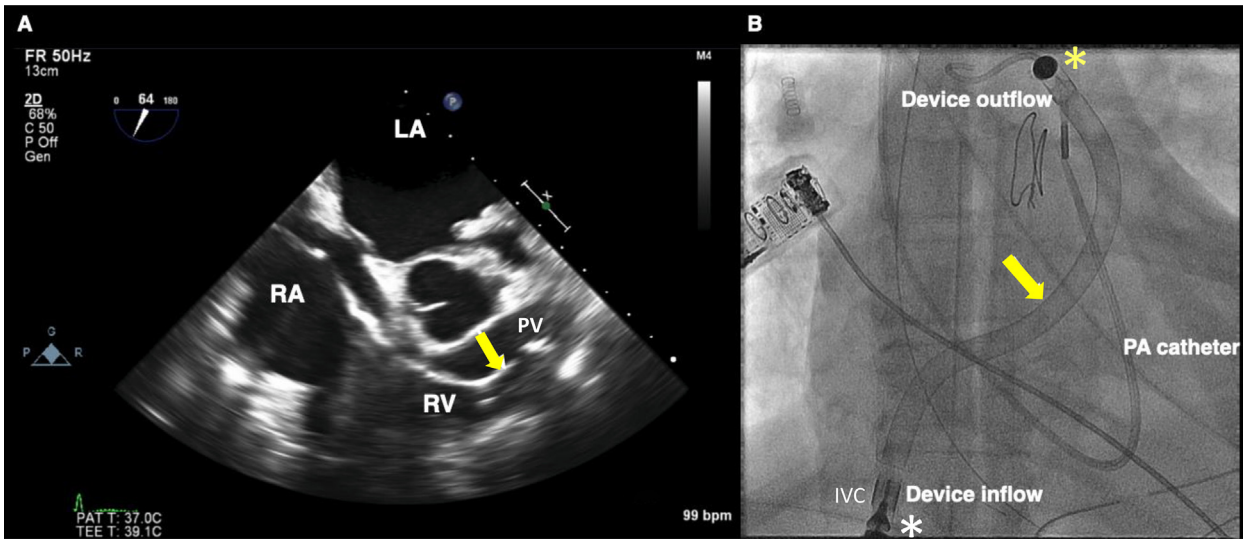


Figure 20 Transesophageal echocardiography assessment of the Impella RP device. **(A)** Midesophageal RV inflow-outflow view shows the device (*yellow arrow*) traversing the TV valve into the RV and across the PV into the PA. **(B)** Fluoroscopy anteroposterior view of the same patient with the device (*yellow arrow*) positioned in the RV from the IVC. The inflow (*white asterisk*) and outflow (*yellow asterisk*) of the device can be seen.

low-flow alarms appear as "Low Flow" or "Suction" on the controller alarm display.

Key Points: LVAD Parameters and HM3 Alarm Types

- Key parameters common to all LVAD consoles, including the HM3, are speed, power, and flow. Left ventricular assist device controller alarms are typically triggered by abnormalities in 1 or more of these parameters.
- Knowledge of a patient's clinical status, in addition to the alarm type, remains helpful to guide echocardiographers during image acquisition and interpretation.
- For clinical problem solving, including for the HM3, it remains useful to divide controller alarms into either low flow or high flow, as each of these is associated with a unique set of differential diagnoses.
- Differentiation between potential causes of alarms requires evaluation of echocardiographic parameters and clinical features.

CLINICAL AND ECHOCARDIOGRAPHIC FINDINGS ASSOCIATED WITH LVAD LOW-FLOW ALARMS

The various conditions that may trigger low-flow alarms are noted above and in Table 6. More recently, outflow cannula obstruction due to kinking, twisting, or acquired obstruction (internal or external to the graft lumen) has been described.[81]

Early postoperative low-flow alarms typically occur due to cardiac tamponade (Supplemental Figure 6), early RVF (Supplemental Figure 7), or hypovolemia. Both cardiac tamponade and RVF after LVAD implantation can be associated with hypotension and an elevated central venous pressure. Echocardiography can help differentiate between these emergencies. We refer readers to the 2015 Guideline[3] and to the Supplemental Material for a complete description of RV dysfunction and tamponade after LVAD implantation and associated low-flow alarms.

Inflow Cannula Obstruction and Low-Flow Alarms

Other causes of low-flow alarms include partial or intermittent mechanical obstruction of the inflow cannula secondary to thrombosis, large vegetations, or endocardial contact that may provoke suction events (Figure 32). Echocardiographic features of inflow cannula obstruction may include the following: visualized thrombus and/or trabeculations near the inflow cannula, abnormally increased color-flow and spectral Doppler inflow cannula velocities (unlikely to be seen in the HVAD due to color Doppler artifact associated with this device), and nonuniform inflow velocity patterns (more applicable to the HM-II). The inflow cannula velocities may be elevated as blood accelerates proximal to the obstruction, whereas outflow graft velocities may be relatively decreased and/or appear to have peak velocity variations. Remember that variation in the peak inflow and outflow cannula velocities in the HM3 device can be seen due to the embedded pulse design (Figure 12). This should not be mistaken for intermittent obstructive physiology.

Mechanical Obstruction of the LVAD Outflow Graft and Low-Flow Alarms

Mechanical obstruction of the outflow graft can result from kinking, malposition, external compression, or thrombosis and as previously described[3] will function similarly to an increase in afterload opposing LVAD forward flow. In patients with the HM3, a unique "twist" mechanism has been described. Prior to May 2018, the HM3 was implanted with the outflow cannula attached to the pump housing with use of a swivel joint to permit easy outflow cannula disconnection, if needed (i.e., at the time of pump removal during heart transplant or with myocardial recovery). Several case series

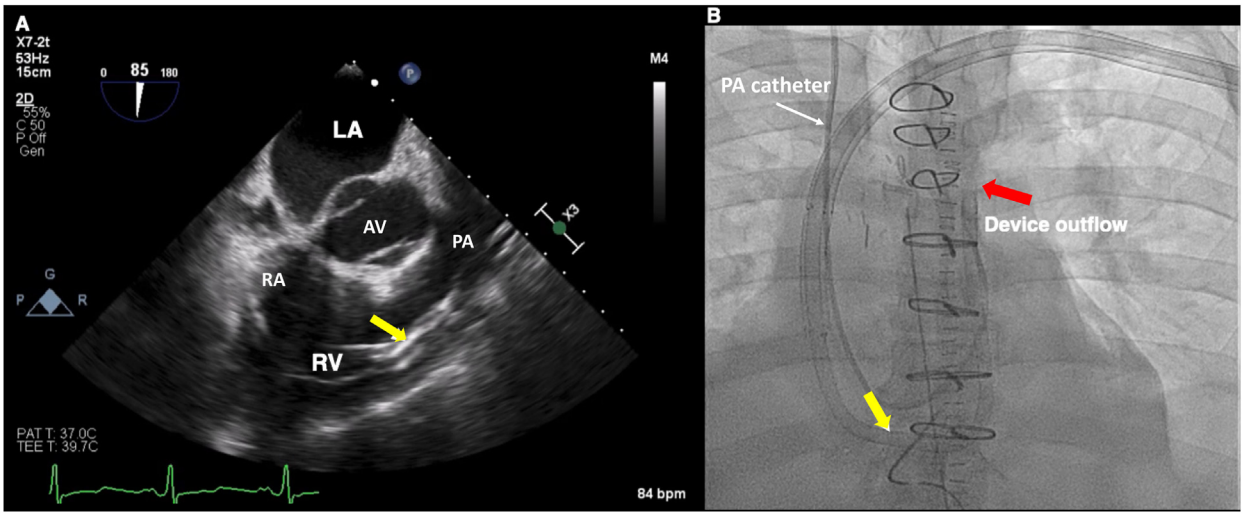


Figure 21 Transesophageal echocardiography assessment of the ProtekDuo cannula. **(A)** Modified midesophageal RV inflow-outflow view showing the device (*yellow arrow*) extending into the RV and across the PV into the PA. **(B)** Fluoroscopy anteroposterior view of the same device (*yellow arrow*) seen entering the RA from the left venous side via the SVC with the device outflow in the PA (*red arrow*). A PA catheter (*white arrow*) from the right IJ vein is also seen.

described twist of the proximal portion of the outflow cannula and acquired impediment to LVAD forward flow.[81] To mitigate this issue the outflow graft clip was designed to prevent any rotation of the outflow graft, thus eliminating the safety concern previously reported. The outflow graft clip has been in use with all new HM3 implants since May 2018 and may be used on patient cases where an outflow graft twist is confirmed and surgical intervention is required. Additional causes of outflow graft narrowing have been

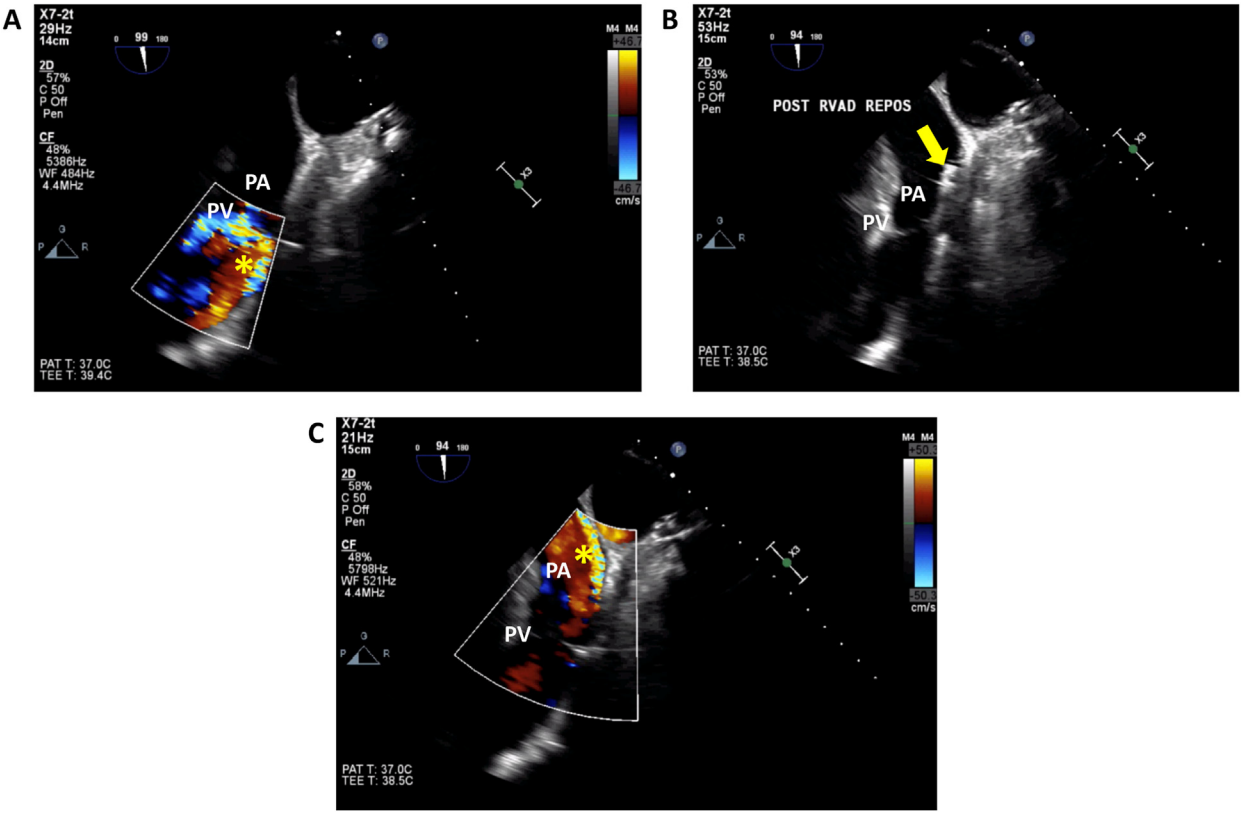


Figure 22 ProtekDuo cannula malposition and correction detection by TEE. **(A)** Upper esophageal aortic arch short-axis view illustrating ProtekDuo cannula migration into the RVOT generating flow seen by CFD (*yellow asterisk*) underneath the PV. **(B)** Upper esophageal aortic arch short-axis view after the cannula (*yellow arrow*) was advanced under fluoroscopic and echocardiographic guidance. The tip of the cannula (*yellow arrow*) can now be seen above the PV and in the PA. **(C)** Upper esophageal aortic arch short-axis view with CFD (*yellow asterisk*) showing flow in the PA.

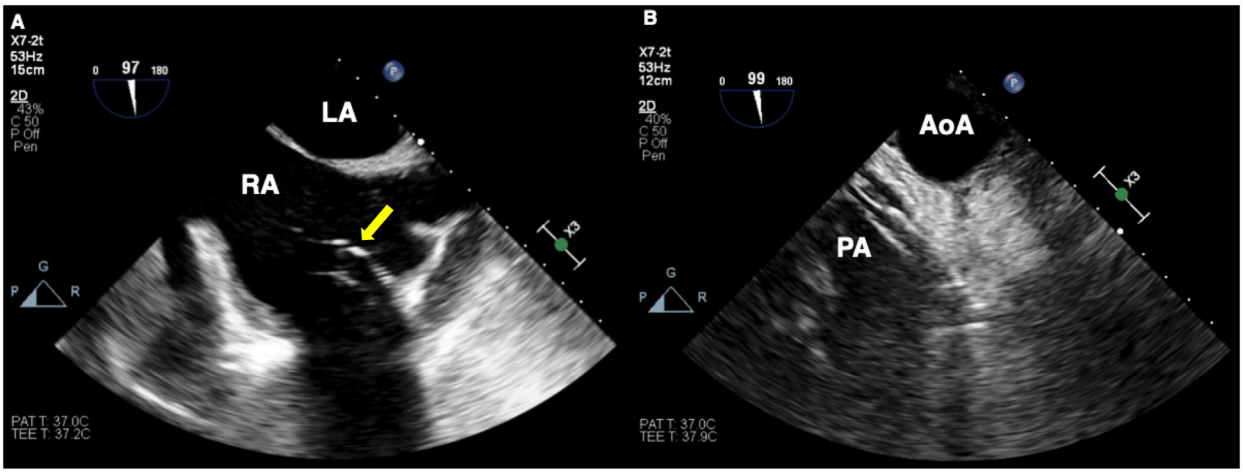


Figure 23 Transesophageal echocardiography assessment of RV assist device cannulas. **(A)** Midesophageal bicaval view shows inflow cannula (*yellow arrow*) seen entering the RA at the level of the RA appendage. **(B)** Upper esophageal AoA short-axis view shows the outflow cannula in the main PA. *AoA*, Aortic arch.

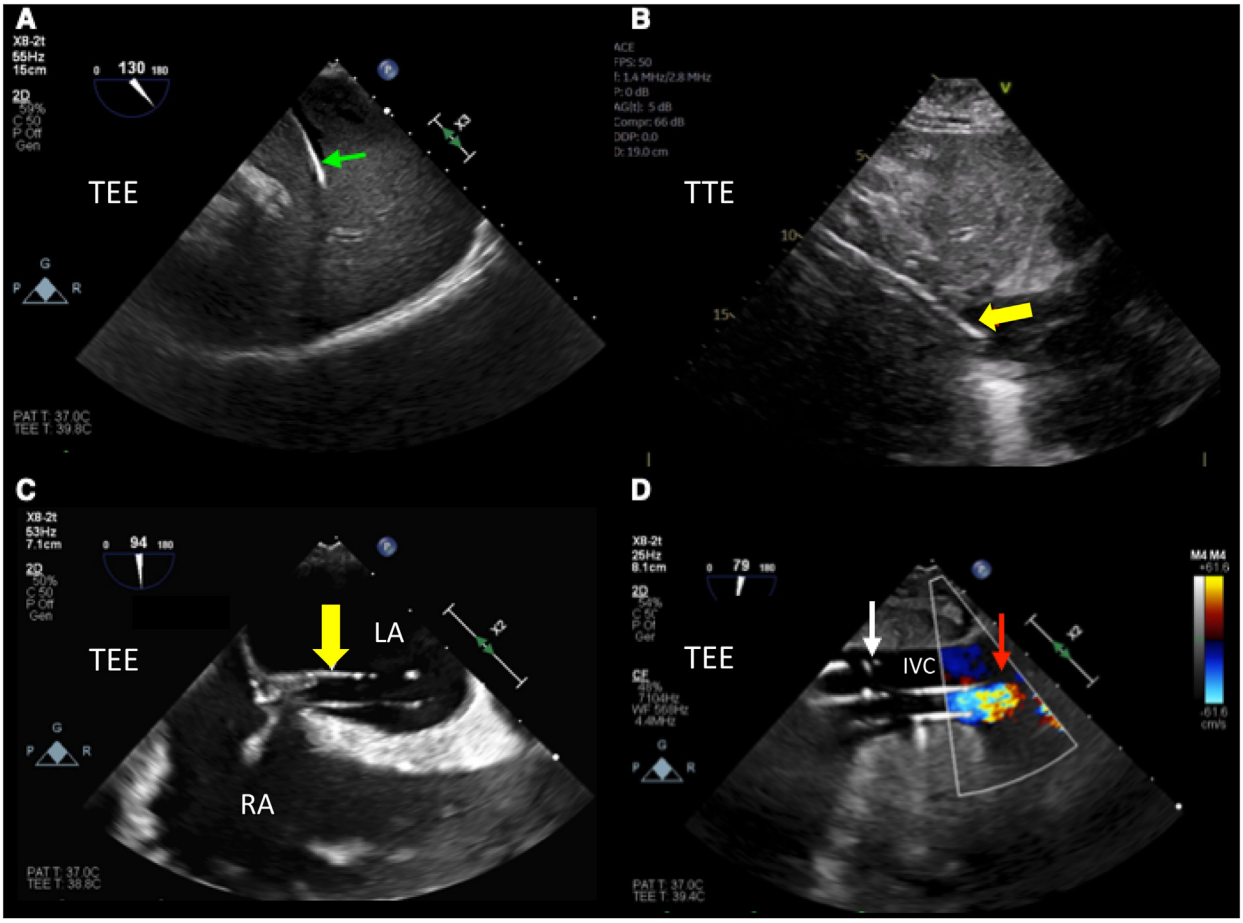


Figure 24 Transesophageal echocardiography and TTE assessment of VV ECMO cannula position. **(A)** Transesophageal echocardiography (nonstandard transgastric view of the liver) with the guidewire (*green arrow*) used for placing a VV ECMO cannula seen engaging a hepatic vein. **(B)** Transthoracic echocardiography (subcostal view of the IVC) VV ECMO cannula (*yellow arrow*) seen by TTE in the IVC at a level below the IVC junction with the RA. **(C)** Transesophageal echocardiography (midesophageal bicaval view) VV ECMO return cannula (*yellow arrow*) malposition with the cannula seen crossing a large PFO and in the LA. While the cannula had been positioned correctly at the time of surgery, it had advanced across the PFO during support. **(D)** Transesophageal echocardiography (nonstandard view of the IVC below the junction with the RA) VV ECMO drainage cannula (*white arrow*) and return cannula (*red arrow*) positioned too close to each other in the IVC, leading to possible recirculation.

reported as a result of accumulation of biodebris either internal or external to the outflow graft.[82]

These specific outflow complications are best defined by CT imaging (see "Multimodality Imaging While on LVAD Support"). Echocardiographic findings are similar to those of inflow cannula obstruction, except that Doppler interrogation of the outflow graft may reveal increased or decreased velocities, depending on the site and degree of obstruction relative to the velocity sampling site. A ramp study may be extremely helpful to screen for suspected outflow cannula obstruction by revealing attenuation of the expected intracardiac flow changes, as measured by RVOT and LVOT velocity-time integral (VTI) or conduit S/D velocity ratios, as well as LV chamber size reduction and AV opening at varying pump speeds.

Key Points: Echocardiographic Findings and LVAD Low-Flow Alarms

- Echocardiography is helpful to define the cause(s) of low-flow alarms including cardiac tamponade, RVF, hypovolemia, and inflow cannula obstruction or malposition.
- Low-flow alarms due to mechanical outflow graft obstruction can result from kinking, malposition, external compression, or thrombosis. These conditions are more challenging to diagnose using echocardiography and are better defined by CT imaging (see "Multimodality Imaging While on LVAD Support").
- Echocardiographic signs of low-flow alarms related to RVF include bowing of the IVS toward the LV during systole and diastole, shifting of the IAS to the left, a dilated IVC without collapsibility, and Doppler measures reflective of hepatic vein flow reversal.
- Cardiac tamponade should be suspected with echocardiographic detection of a pericardial effusion or organized pericardial clot in conjunction with LVAD alarms and a small LV and/or RV chamber.
- Echocardiographic features of inflow cannula obstruction may include visualized thrombus and/or trabeculations near the inflow cannula, abnormally increased inflow cannula velocities, and/or dynamic interaction of the inflow cannula and endocardium.

ECHOCARDIOGRAPHIC ASSESSMENT OF ABNORMAL TMCS DEVICE ALARMS

Impella Device Troubleshooting

Echocardiographic confirmation of adequate position and function is recommended (1) in the setting of lower than expected flows for the level of support provided, unresolved suction events or position-related alarms, or to confirm a suspected air leak, (2) when worsened RV function is suspected, (3) after significant patient movements or adjustment of the catheter position, (4) after cardiopulmonary resuscitation with defibrillation or chest compressions, (5) to assess for myocardial recovery while on support, and (6) if hemolysis is detected. If device migration is suspected based on clinical, hemodynamic, metabolic, and device console parameters, it is possible that the inlet and the outlet may be both located on the same side of the AV, resulting in blood recirculation and ineffective forward flow and LV unloading. Figure 33 illustrates the use of TTE to detect Impella device-related complications.

In addition, for the Impella devices, the aortic or ventricular placement signal along with information about motor current may suggest the device is in the incorrect position, including being too far into the LV. Recommended actions include reducing the flow rate to P2 (low level of support) and using echocardiographic guidance to reposition the pump until the inlet area is positioned adequately below the aortic annulus.

Extracorporeal Membrane Oxygenation Device Troubleshooting

During VV ECMO support, the role of echocardiography is somewhat limited. Nonetheless, it can identify causes for low ECMO flows or hypoxemia and monitor ventricular function. Low ECMO flows can be due to hypovolemia (e.g., collapsed heart chambers, IVC wall collapsing around the drainage cannula), pericardial effusion and cardiac tamponade, or cannula displacement. In the presence of adequate VV ECMO flows, hypoxemia can be due to cannula displacement resulting in recirculation.

Echocardiography during VA ECMO support is paramount in monitoring the adequacy of support, diagnosing complications including those related to thrombosis (Figure 34), and assessing the response to ECMO support. Hemodynamic and echocardiographic monitoring of adequate LV unloading is important, especially after initiation of VA ECMO support. The LV and LA should be assessed for size, presence of stasis and thrombus formation, presence and severity of MR, and frequency of AV opening. In the absence of AV opening, thrombus can form in the aortic root, preventing adequate coronary blood flow and myocardial oxygen delivery. Newly inserted prosthetic valves in the mitral or aortic position are particularly at risk for thrombosis, which may impede adequate valve function.[83]

Causes of VA ECMO low flow include hypovolemia (like other devices), cannula displacement (especially the drainage cannula), partial occlusion of the drainage cannula by adjacent structures or thrombus, and cardiac tamponade. The evaluation for pericardial effusion and pericardial clot should be performed in several imaging views, as these fluid collections may be loculated rather than circumferential. At all times during ECMO support, echocardiographic findings should be integrated with hemodynamic, clinical, and ventilatory parameters.

Cardiac POCUS and TMCS Troubleshooting

Cardiac POCUS provides rapid bedside diagnosis of important cardiovascular pathology and is performed by a growing number of users in a variety of clinical and teaching settings.[84] Given the focused and potentially frequent need to help the TMCS troubleshooting, some centers have incorporated an ultrasound-assisted physical examination and cardiac POCUS with a limited imaging protocol to detect or characterize specific findings or to facilitate serial assessments in a timely fashion. Examples that highlight the potential use of POCUS in the setting of TMCS include screening for stable Impella device position or to document device malposition and AV opening and to rule out device malfunction due to compression from pericardial effusion. There are no published reports that define the safety and efficacy of incorporating POCUS to guide TMCS management.

Ultrasound-Enhancing Agent Use in Patients on TMCS

The use of UEAs has become an integral component of echocardiography practice including in critically ill patients. Ultrasound-enhancing

agents have been shown to improve the assessment of ventricular function and to reduce the need for downstream diagnostic testing.[85] Specifically, UEAs should not be withheld based on any diagnosis or comorbidity. Although there are little data that define the safety and efficacy of UEAs in patients on TMCS (including IABPs, Impella devices, the TandemHeart, and right-sided percutaneous support devices), the use of UEAs in patients supported by these devices is not contraindicated and should be used if needed to better assess LV function. However, there remains understandable caution surrounding their use in patients supported by ECMO as UEAs may potentially activate the protective integrated air bubble alarms in certain devices, which could trigger interventions to disable flow. This could lead to a pump shutdown because of activation of additional safety device algorithms, and unless this alarm is cleared, the resultant cessation of flow and/or oxygenation can result in rapid perfusion compromise and/or desaturation and potentially in cardiac and/or hypoxic arrest. Although mitigation strategies (e.g., inactivation of the device bubble algorithm and/or activation of an override algorithm to prevent decrements in pump flow and pump stoppage) exist to facilitate the use UEA in patients supported by ECMO, there remains a paucity of safety data to support widespread use of UEA in this patient population.

Key Points: Impella and ECMO Device Troubleshooting, Cardiac POCUS, and UEA Use

- Echocardiography can be useful to assess volume status, evaluate catheter positioning and guide repositioning if necessary, and screen for worsening RV function while on Impella support.
- Echocardiography can be useful to differentiate causes of VA ECMO low flow including hypovolemia (like other devices), drainage cannula displacement, partial occlusion of the drainage cannula by adjacent structures or thrombus, and cardiac tamponade.
- The LV and LA should be assessed by echocardiography for size, presence of blood stasis and thrombus formation, presence and severity of MR, and frequency of AV opening while on VA ECMO support.
- Cardiac POCUS can be used to detect Impella device position and AV opening and to rule out device malfunction due to external compression.
- Training and continuous quality improvement are crucial components for all forms of cardiac ultrasound including POCUS when used to monitor patients supported by TMCS.
- Like their use in patients supported by durable LVADs, UEAs may be considered in patients supported by TMCS including IABPs, Impella and TandemHeart devices, and percutaneous RV support devices.
- UEAs should not be used in patients on ECMO devices, unless under the supervision of experienced perfusionists and clinicians due to possible interference with air bubble alarms and device function.

ECHOCARDIOGRAPHIC ASSESSMENT OF MYOCARDIAL RECOVERY ON LVAD AND TEMPORARY MCS

Myocardial Recovery With LVAD Support

Myocardial recovery after LVAD implantation has been reported by several investigators.[86,87] Overall, a small percentage of patients recover sufficient native LV function to permit LVAD explantation without the need for HT or LVAD replacement.[87] More recently, a prospective multicenter nonrandomized study (RESTAGE-HF [Remission from Stage D Heart Failure]) reported a 40% rate of LVAD explantation (16 out of 40 highly select enrolled patients) and demonstrated protocol feasibility and reproducibility, with explantations occurring in all 6 participating sites.[88]

As reported in the 2015 Guideline,[3] evidence of myocardial recovery while on LVAD support typically includes satisfactory hemodynamic and echocardiographic findings during an LVAD turndown study. Proposed echocardiographic criteria that define myocardial recovery measured at 6,000 rpm (net zero flow in patients supported by the HM-II) for 15 minutes include an LVIDd <60 mm, LV end-systolic diameter < 50 mm, and LVEF >45% in addition to hemodynamics consistent with normal ventricular filling pressure and cardiac output and a maximal oxygen consumption with exercise >16 mL/kg/min.[88] There are limited case reports with removal of the HM3 following myocardial recovery.[89-91]

The following basic concepts can be used as a framework to guide decision-making related to this important aspect of LVAD management in highly selected patients. For the HM-II, the study starts at 8,000 rpm and the speed is then decreased every 3 minutes by 400 rpm until the final stage at 6,000 rpm. For the HM3, the initial step is 5,000 rpm, and the speed is reduced every 3 minutes by 100 rpm to a final speed of 4,000 rpm. For HVAD, the initial step is 2,400 rpm, and the speed is reduced every 3 minutes by 100 rpm to a final speed of 1,800 rpm. At every step, all TTE and hemodynamic parameters are recorded.

Myocardial Recovery With TMCS

Although very few studies report on the criteria for weaning to guide TMCS deescalation and explantation, general principles apply to all the TMCS devices. The readiness to deescalate support includes signs of end-organ recovery, hemodynamic stability, and increased native cardiac output coupled with echocardiographic evidence of myocardial recovery (e.g., LVOT VTI ≥12 cm, LVEF >25%, lateral mitral annulus systolic velocity [s′] ≥6 cm) at low levels of inotropic, vasopressor, and device support maintained over several hours before explantation is attempted.[92] The timing of the weaning initiation and the stepwise decrease in device support should be tailored based on the etiology of CS and the required level of support needed to maintain hemodynamic stability. After explantation of the TMCS device, a comprehensive echocardiogram should be performed to establish a new baseline of ventricular and valvular function, as well as specifically evaluate for new or worsened AR or MR due to possible direct damage from the device.[92] Specific to the TandemHeart, the presence and degree of shunting across the iatrogenic ASD at the time of device removal should be noted, and closure of the defect should be considered in patients at risk for systemic embolization or right-to-left shunt.[93]

Limited data are available for weaning and explantation protocols for patients supported by RV TMCS. While supported on Impella RP devices, patients in the RECOVER RIGHT trial underwent weaning of the device in a stepwise manner, with a decrease in flow by 0.5 to 1 L/min every 2 to 3 hours. Adequate right-sided hemodynamics (central venous pressure <12 mm Hg, increased pulmonary arterial pressure waveform amplitude, mixed venous oxygen saturation >55%) and improved echocardiographic indices of RV systolic function at every level of support will indicate the readiness for explantation of the device.[92,94]

Echocardiography is an invaluable diagnostic and dynamic monitoring tool in all aspects of ECMO support including during weaning.[53-55] The decision to wean from VA ECMO support is complex and should be based on clinical, hemodynamic, and echocardiographic data. Strategies for assessing readiness to wean and readiness to explant or deescalate ECMO support have been recently reviewed.[92,95,96] Echocardiographic parameters identified as predictors of successful weaning from VA ECMO support include qualitative and quantitative descriptors of LV function (e.g., LVEF ≥20%-25%, LVOT VTI ≥10 cm, and MV lateral s′ ≥6 cm/sec),[97] RV function (e.g., RV free wall strain < −10.9 %, RVEF >24.6%[98]), and RV-PA coupling.[99] During a successful weaning, a patient is hemodynamically stable and is without requirement for a significant increase in inotropic or vasopressor support. Expected echocardiographic findings to support a successful weaning include evidence of recruitment of LV and/or RV function (qualitatively or quantitatively) and a recruitment of stroke volume demonstrated with echocardiography by an increase in LVOT or RVOT VTI.

Key Points: Myocardial Recovery With LVAD and TMCS

- The decision to wean from LVAD or TMCS is complex and should be based on clinical, hemodynamic, and echocardiographic data.
- Proposed echocardiographic criteria that help to define myocardial recovery on HM3 support include an LVIDd <60 mm, LV end-systolic diameter <50 mm, and LVEF >45% at low levels of support (e.g., net zero flow at 4,000 rpm).
- Expected echocardiographic findings to support a successful TMCS weaning include evidence of recruitment of LV and/or RV function (qualitatively or quantitatively) and a recruitment of stroke volume demonstrated by an increase in LVOT or RVOT VTI.
- After explantation of the TMCS device, a comprehensive echocardiogram should be performed to establish a new baseline of ventricular and valvular function, as well as specifically evaluate for device-induced new or worsened AR or MR.

MULTIMODALITY IMAGING WHILE ON LVAD SUPPORT

Although echocardiography is the first-line imaging modality to evaluate suspected LVAD malfunction, an accurate anatomical evaluation of the entirety of the LVAD, including the pump and entire outflow cannula, is not possible even with TEE. When needed, additional noninvasive imaging can help identify anatomic complications including infections.

Cardiac CT and Technical Considerations With LVAD Imaging

Cardiac CT to define the LVAD system can be performed with contrast (Figure 35) or without contrast (Figure 36). If a CT scan is being performed to document the position of the inflow cannula or kinking of the outflow graft, a noncontrast CT may suffice. Use of contrast, however, improves visualization of the LVAD components and surrounding structures (Figure 37). It is important to emphasize that electrocardiogram (ECG) gating is essential to avoid motion artifacts to optimize examination of the relationship of the LVAD with the heart and aorta. Premedication for heart rate control with beta-blockers or ivabradine is usually safe but rarely necessary unless a coronary evaluation is needed. When information is required to examine RV function, dynamic cannula suction, or valvular abnormalities, retrospective gating with or without dose modulation is typically used. However, no dose modulation is preferable, given the fact that beam-hardening artifact from the LVAD produces significant image degradation and noise that could diminish diagnostic ability. Additional image acquisition details are included in the Supplemental Material.

One of the main challenges to LVAD imaging is that the hardware components have highly attenuating materials (titanium and its alloys) that lead to unavoidable artifact due to beam hardening, photon starvation, inconsistent projection data (because of cardiac motion), and partial volume effects. Anecdotally, the artifacts appear to be worse with the HVAD device followed by HM3 and then HM-II. In some cases, use of an iterative metal artifact reduction algorithm can reduce metallic artifacts in CT scans[100] (Figure 38). Contrast window adjustment with level/width at around 1,000/3,000 could potentially permit visualization within the pump housing to assess the rotor (Figure 39).

Cardiac CT and RV Assessment

Electrocardiogram-gated CTA provides the best examination of RV structure and function. Right ventricular size can be easily obtained by 2D measurement of the maximal distance between the ventricular endocardium of the lateral wall and the IVS perpendicular to the long axis of the heart in a reconstructed 4-chamber view. Accurate 3D RV end-diastolic and systolic volumes can be measured semiautomatically to calculate RVEF[101] (Supplemental Figure 8). These measurements are made in accordance with ASE guidelines as CT-specific guidelines do not exist.

In a study of 36 patients (86% HM-II), evaluation of RVEF was highly feasible (98%) with excellent interobserver reliability (intraclass correlation coefficient = 0.89). On the other hand, feasibility of echocardiographic evaluation was much lower, and a complete visualization of RV endocardium was feasible in only 15% of patients with more limited interobserver reliability (intraclass correlation coefficient = 0.57).[102] Similar to echocardiography and cardiac magnetic resonance imaging, diastolic septal flattening or bowing may be indicative of significant RV dysfunction due to volume overload caused by pulmonary regurgitation (PR) and/or TR. Reflux of contrast medium into the IVC is considered a specific but insensitive sign of right-sided heart disease/RVF at low-contrast injections, although the usefulness decreases with high injection rates.

Cardiac CT and Inflow Cannula Assessment

It remains important to highlight a lack of consensus on imaging criteria (echocardiographic or CT) that define inflow cannula

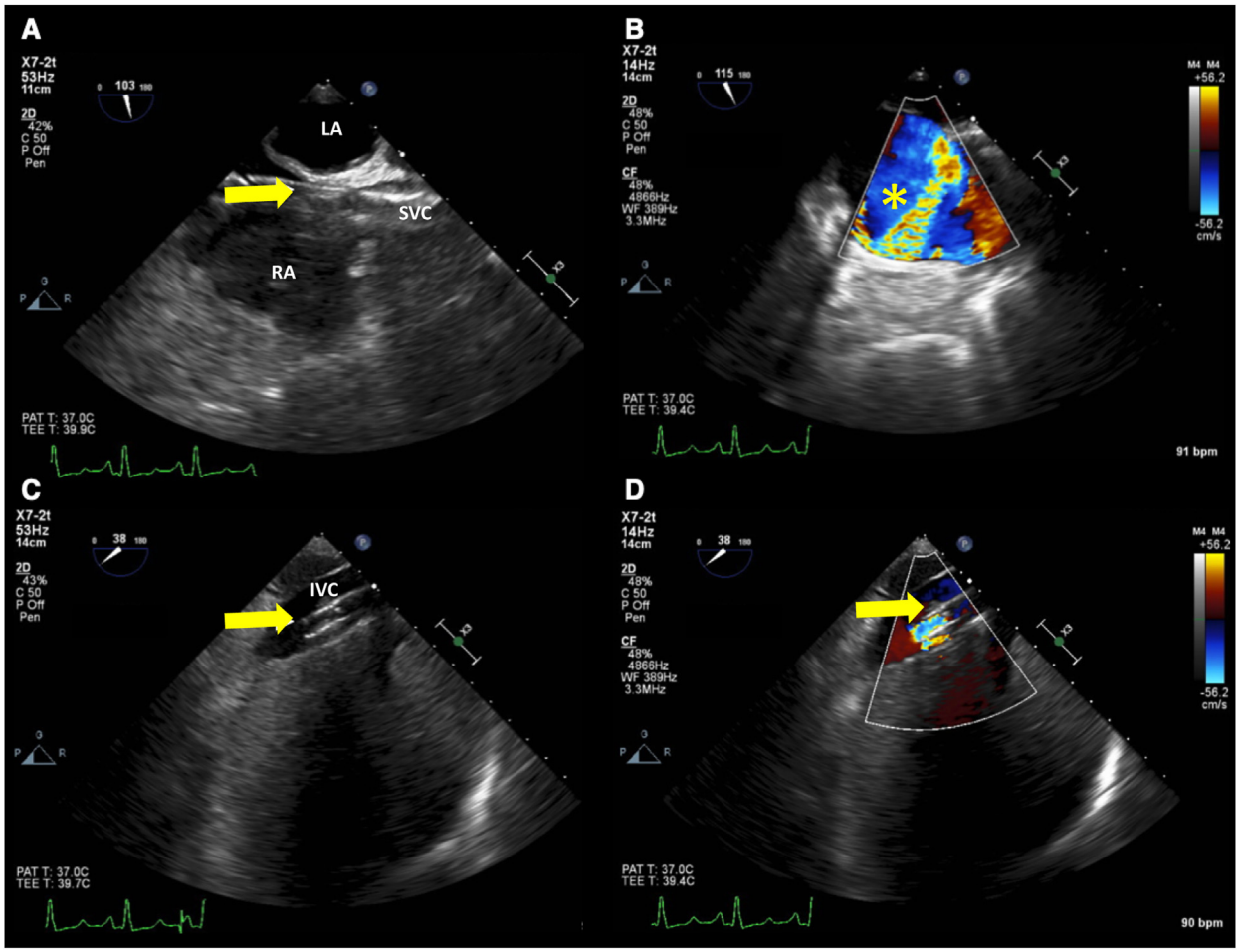


Figure 25 Dual lumen bicaval cannula for VV ECMO. **(A)** Midesophageal bicaval view shows the cannula (*yellow arrow*) advancing from the SVC into the RA and toward the IVC. **(B)** Bicaval view illustrating flow from the return port (*yellow asterisk*) of the device in the lower portion of the RA directed toward the TV. **(C)** The tip of the cannula (*yellow arrow*) is seen in the IVC. **(D)** Unobstructed blood flow shown by CFD into the cannula ports is then directed to the pump and oxygenator (not shown here) to be returned to the RA as illustrated in *panel B*.

malposition. It is not uncommon to see a deviation of the inflow cannula from the ideal position (which is directed toward the MV and parallel to the LVOT) in stable asymptomatic patients with normal device flow parameters. Malposition of the inflow cannula can be seen in all 3 LVADs and can lead to LVAD suction events (including mechanical ventricular tachycardia) with myocardial tissue becoming sucked continuously or intermittently into the inflow cannula (Figure 40). As previously discussed, the MCS team may elect to lower the pump speed to avoid this complication, even at the expense of partial LV unloading. Two CT-based studies showed a correlation of adverse events with inflow cannula position and obstruction.[103,104] Patients supported by the HM-II had a higher incidence of an off-axis cannula position and a higher incidence of pump thrombosis compared to patients supported by the HVAD.[104]

Cardiac CT and Outflow Cannula Assessment

Cardiac CT is particularly useful in the assessment of the outflow graft, especially in situations where low-flow alarms are related to outflow graft kinking or obstruction by intraluminal thrombus or external compression from proteinaceous fluid buildup between the bend relief structure and the outflow graft. A defective bend relief connector can cause outflow graft twisting along its own axis.[81] In addition, CCT datasets can be utilized to plan or guide stenting or surgical release of the acquired kink.[105] The figures demonstrate examples of LVAD outflow graft complications detected by CCT including outflow graft kinking (Figure 37B1 and B2), twist (Figure 41A and B), and bend relief disconnect (Figure 41C).

Cardiac CT and Thrombus Detection

Thrombosis during LVAD support could occur at the level of the inflow cannula, within the pump, and within the outflow graft.[106] These patients may present with low-flow alarms. Detection of thrombus within the pump with current technology is challenging. A study by Tran *et al.*[107] showed that CCT has low sensitivity but high specificity in diagnosing device thrombosis. Inflow cannula and outflow graft thrombosis is more easily detected and can appear as

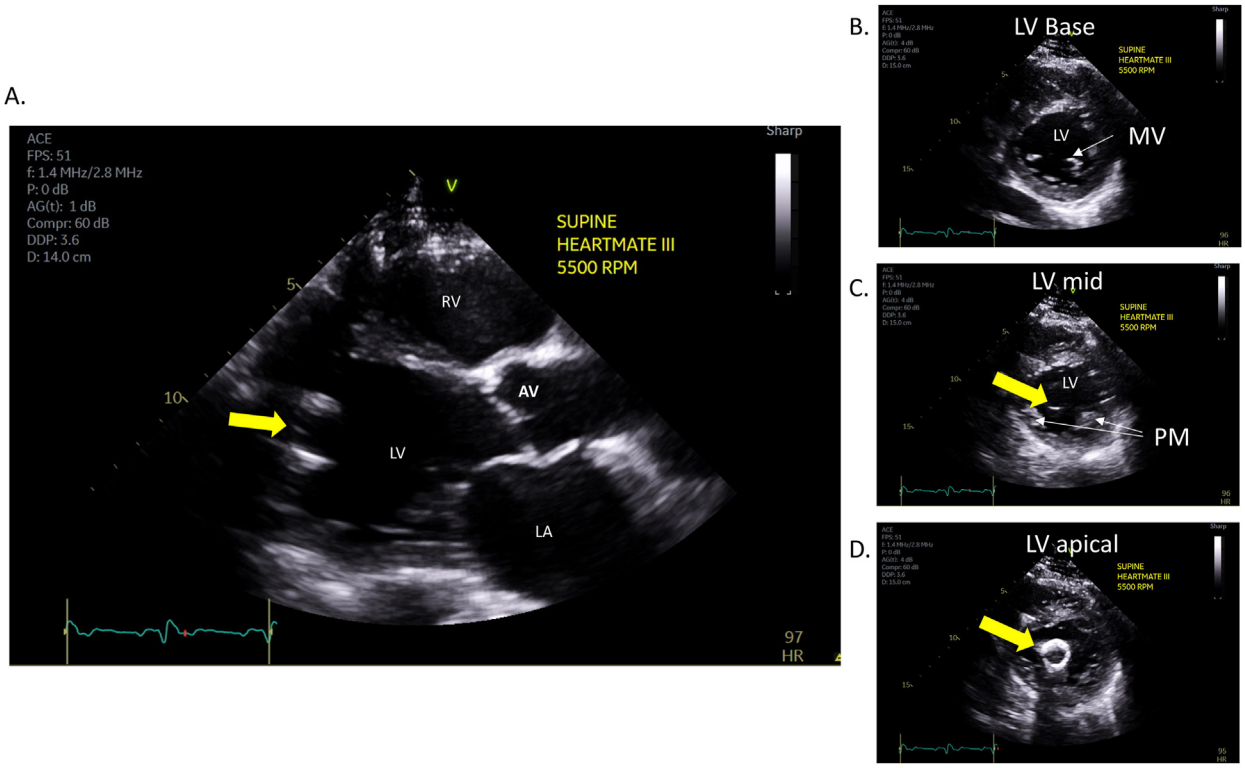


Figure 26 Transthoracic echocardiography illustration of normal HM3 apical inflow cannula position. **(A)** Parasternal long-axis view with the inflow cannula (*yellow arrow*) directed toward the anterior MV leaflet and LVOT parallel to the IVS free of interaction with adjacent structures. **(B)** Parasternal short-axis view with visualization of the base of the LV with MV apparatus evident and absence of the inflow cannula. **(C)** Parasternal short-axis mid-LV view with noted papillary muscles and intermittent visualization of the inflow cannula (*yellow arrow*). **(D)** Parasternal short-axis apical view with complete visualization of the inflow cannula (*yellow arrow*) as a full echodense circle positioned in the middle of the distal LV. *PM*, Papillary muscle.

low attenuation material therein. Careful "windowing" is needed to differentiate thrombus from device-related beam-hardening artifact, particularly near the proximal portion of the cannula. In addition to device-related thrombosis, aortic thrombus can be seen by CCT. One or more aortic sinuses can be involved. Extension of thrombus into the coronary arteries is an uncommon cause of LVAD-related acute coronary syndrome or acute myocardial infarction (Figure 42).

Cardiac CT and LVAD-Associated AR

Cardiac CT can be used to accurately assess the degree of AV opening and in the setting of AR can be used to quantify the regurgitant orifice area. In selected patients being considered for an intervention to treat LVAD-associated significant AR, CCT can guide the surgical or percutaneous intervention planning.[77] One study looked at the outflow graft orientation with development of AR in 23 patients. In this study a higher outflow graft-to-aortic angle was associated with development of AR.[108]

Cardiac CT and LVAD Explant or Exchange Considerations

Computed tomography scanning can be very helpful at the time of surgical explantation for recovery, device exchange, or for HT, particularly to determine the position of the inflow and outflow cannulas[109] and any bypass grafts or proximity of other cardiac structures to the sternum— situations where bypass time and patient morbidity could be adversely affected.

Applications of Nuclear Imaging in Patients With LVADs

An expanding role for nuclear imaging methods in the management of cardiac infections is increasingly recognized.[110] Although TTE and/or TEE can be helpful to screen for the source of infection in patients supported by LVADs with good visualization of the outflow cannula anastomosis site, intracardiac leads, and native or prosthetic valves, echocardiography does not permit visualization of the peripheral or central LVAD components including the driveline, the pump itself, or most of the outflow cannula. Positron emission tomography with 18-

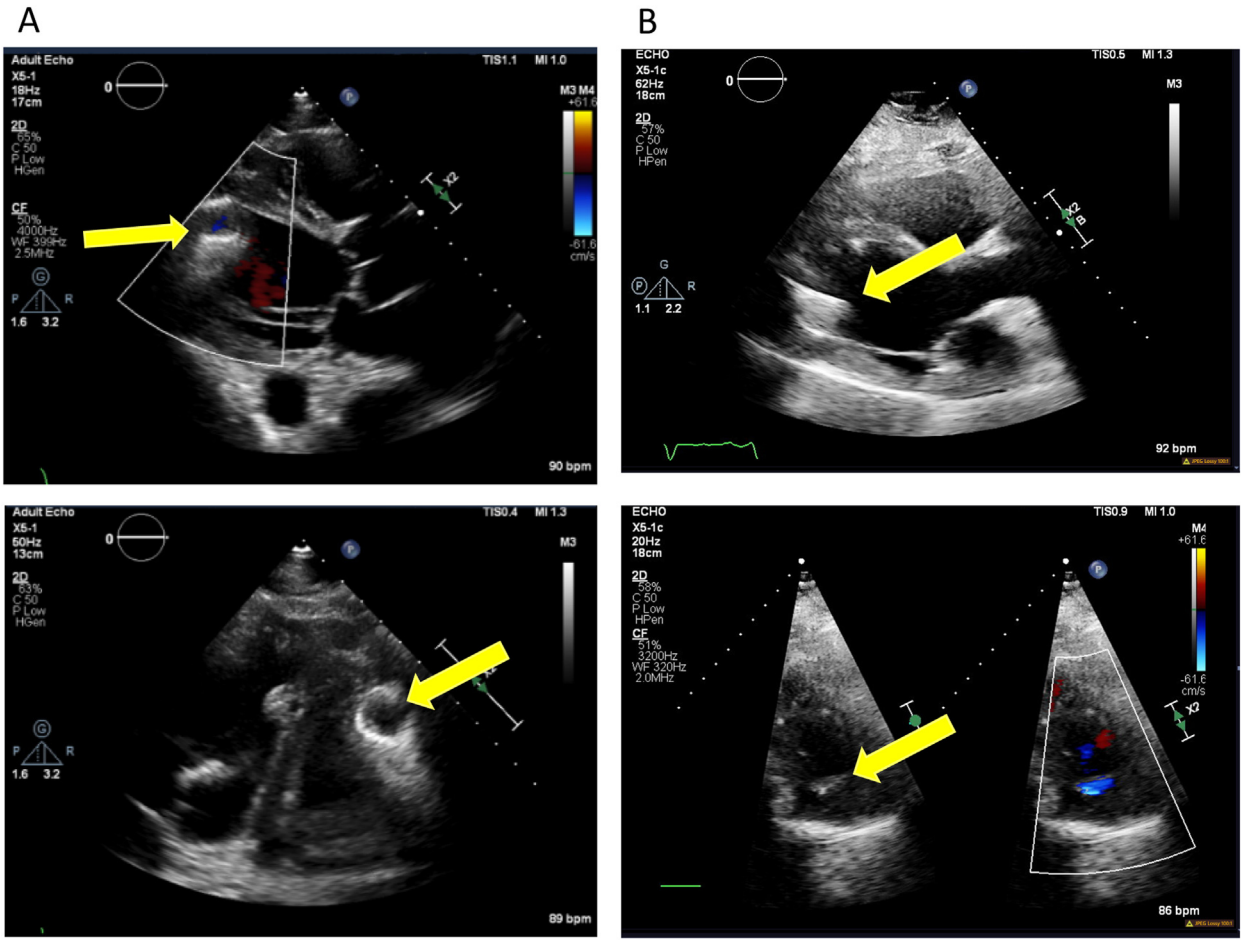


Figure 27 Transthoracic echocardiography illustration of HM3 inflow cannula malposition. **(A)** *Upper panel*: parasternal long-axis view shows the HM3 inflow cannula (*yellow arrow*) positioned in the apex and directed toward the distal anteroseptal wall. *Lower panel*: short-axis view shows the inflow cannula (*yellow arrow*) in the anterior apical position near the endocardium. The patient had frequent PI events and intermittent low-flow alarms. **(B)** *Upper panel*: parasternal long-axis view shows the inflow cannula (*yellow arrow*) positioned in the posterior aspect of the LV. *Lower panel*: short-axis view confirms the inflow cannula (*yellow arrow*) positioned posteriorly and near the endocardium. The patient had frequent PI events with frequent pump speed spin-downs to the lower set speed consistent with LVAD suction.

F-fluorodeoxyglucose (FDG) has established value in the diagnosis of prosthetic valve endocarditis with sensitivity greater than echocardiographic methods.[111] Emerging data now support the use of FDG PET in the management of suspected infection in patients with LVADs. Positron emission tomography-CT is a tomographic modality that allows evaluation of all LVAD components including the inflow and outflow cannulas, pump, and driveline. Several published reports have defined the utility of FDG PET for the diagnosis of LVAD infection.[112-120] A recent meta-analysis across more than 200 patients in 8 studies showed a pooled sensitivity of 0.95 (95% CI, 0.89-0.97) and pooled specificity of 0.91 (95% CI, 0.54-0.99).[121] Similar diagnostic parameters were seen in separate analyses for both the pump and the drivelines. Although less abundant, there are also increasing data on the use of this information for treatment planning and to help define prognosis.[112,118,119,122] In general, a central infection, defined as involvement of the pump itself and/or the outflow cannula, is associated with a worse prognosis than peripheral (driveline) involvement alone.

Performing these studies requires careful attention to patient preparation, imaging technique, and interpretation. It is generally helpful to suppress myocardial uptake of FDG. Imaging should cover the entire LVAD system, and consideration of whole-body imaging should be given as FDG PET is an excellent method to identify metastatic foci of infection (Figure 43). In general, PET-CT is preferable to PET with dedicated line source attenuation correction. However, careful attention must be paid to avoid overcalling artifactual uptake caused by dense metal devices. To differentiate a true versus

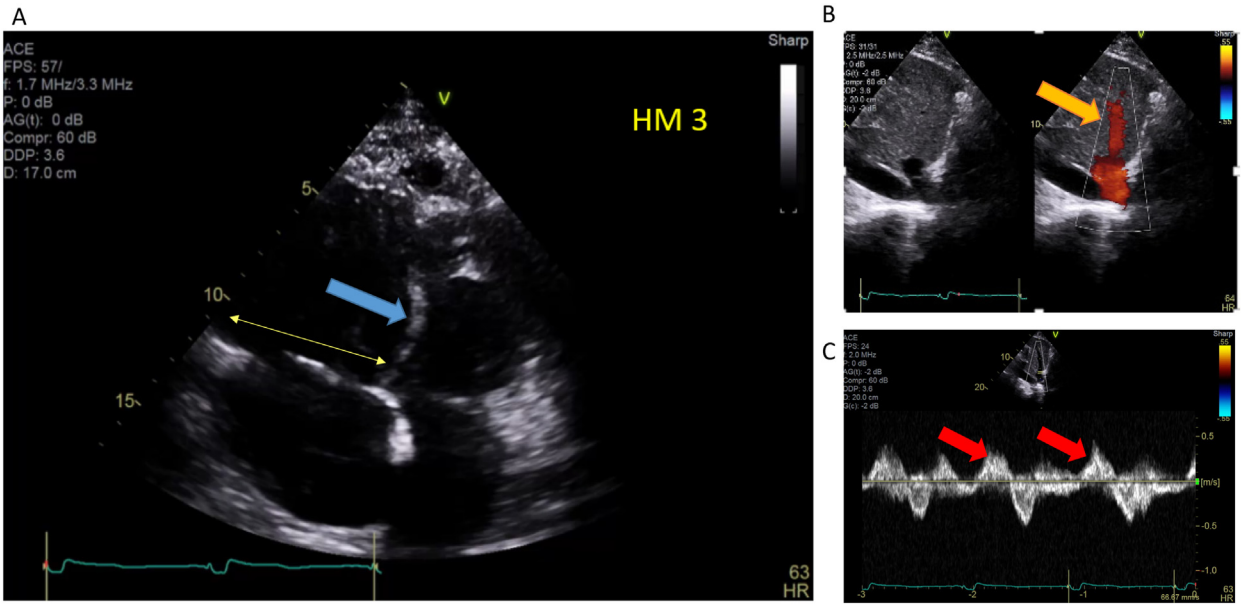


Figure 28 Transthoracic echocardiography illustration of late RVF on HM3 Support. (**A**) Apical 4-chamber view with severe dilation of the RV (*double-headed yellow arrow*), which is greater than the size of the LV, with persistent bowing of the IVS toward the left during systole and diastole (*blue arrow*). See movie 4. **(B)** Same patient with color Doppler demonstration of flow reversal in the hepatic vein (*orange arrow*). (**C**) Same patient with PW Doppler assessment of the hepatic vein demonstrating systolic flow reversal (*red arrows*) consistent with severe TR related to RVF and elevated RA pressure.

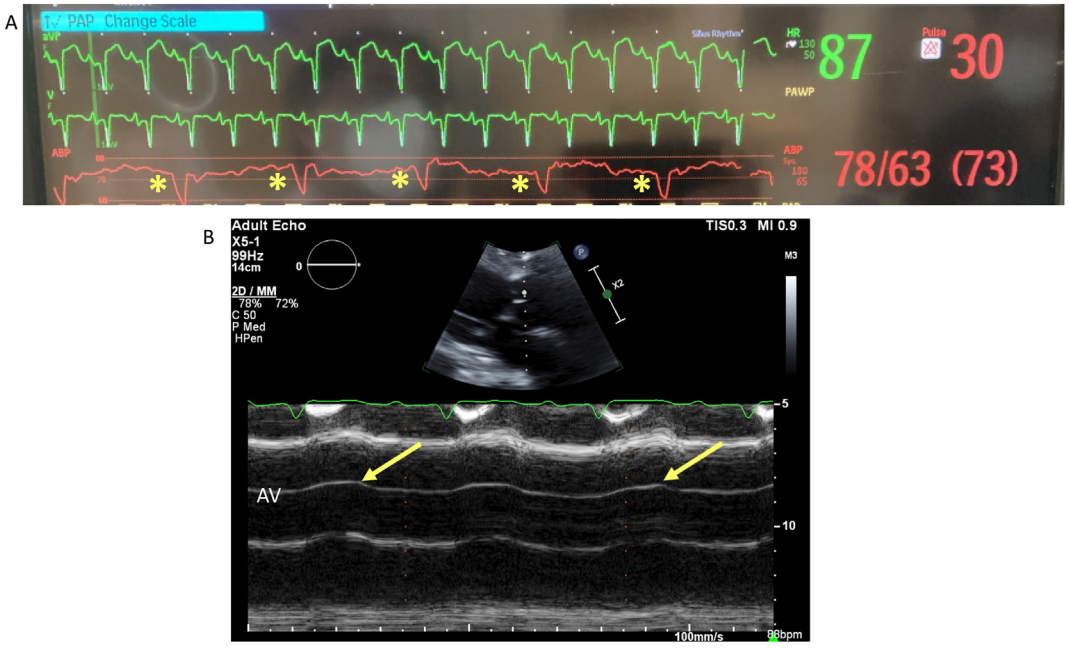


Figure 29 Example of HM3 and persistent AV closure. **(A)** Arterial line BP assessment with a mild decrement (within 10 to 15 mm Hg) in BP every 2 seconds (*yellow asterisk*) attributed to the underlying artificial pulse (see text for description). **(B)** Parasternal long-axis M-mode evaluation at the coapting AV cusps (*yellow arrows*) in the same patient at the same time with no AV opening noted illustrating the artificial pulse may not cause the AV to fully open.

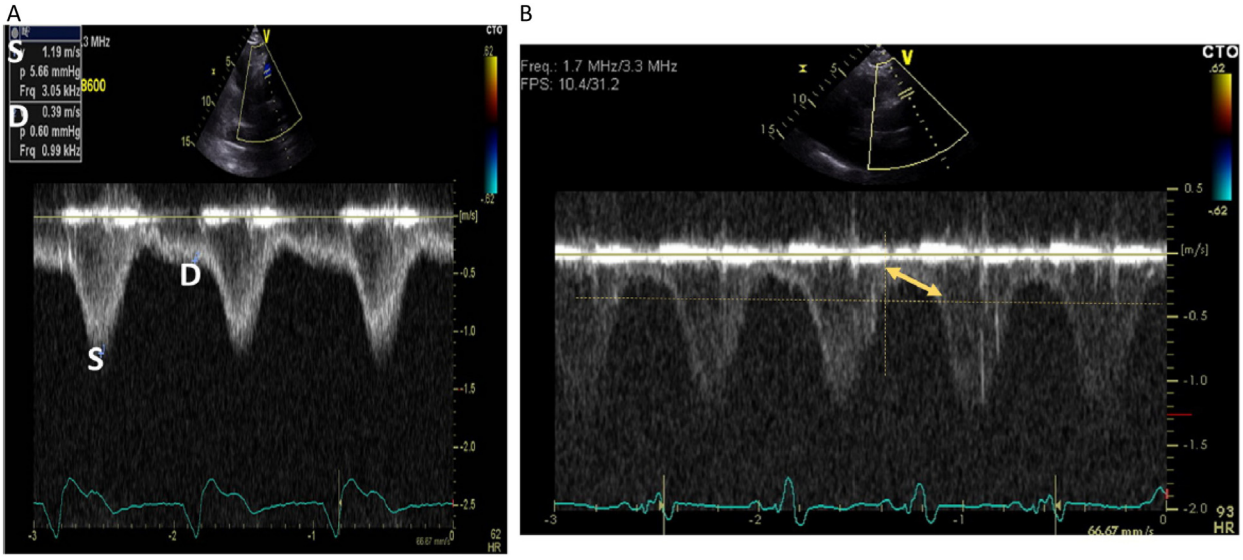


Figure 30 Transthoracic echocardiography LVAD outflow cannula Doppler assessment to define AR. Images are typically obtained from the high parasternal view with PW spectral Doppler examination within 1 to 1.5 cm from the site of anastomosis of the outflow cannula. **(A)** Illustration of the calculation of the S/D ratio obtained by measuring the peak systolic velocity (1.19 m/sec) and dividing by the peak end-diastolic velocity (0.39 m/sec), which equates to a value of 3.0, with moderate or greater AR more likely when the S/D ratio <5.0 (see text). **(B)** Illustration of the calculation of the diastolic acceleration, obtained by measuring the diastolic slope from the onset of diastole to end-diastole (*double-headed yellow arrow*) with significant AR more likely (see text) when the diastolic acceleration is >49.0 cm/sec^2. Adapted figure from reference 74. *D*, Diastole; *S*, systole.

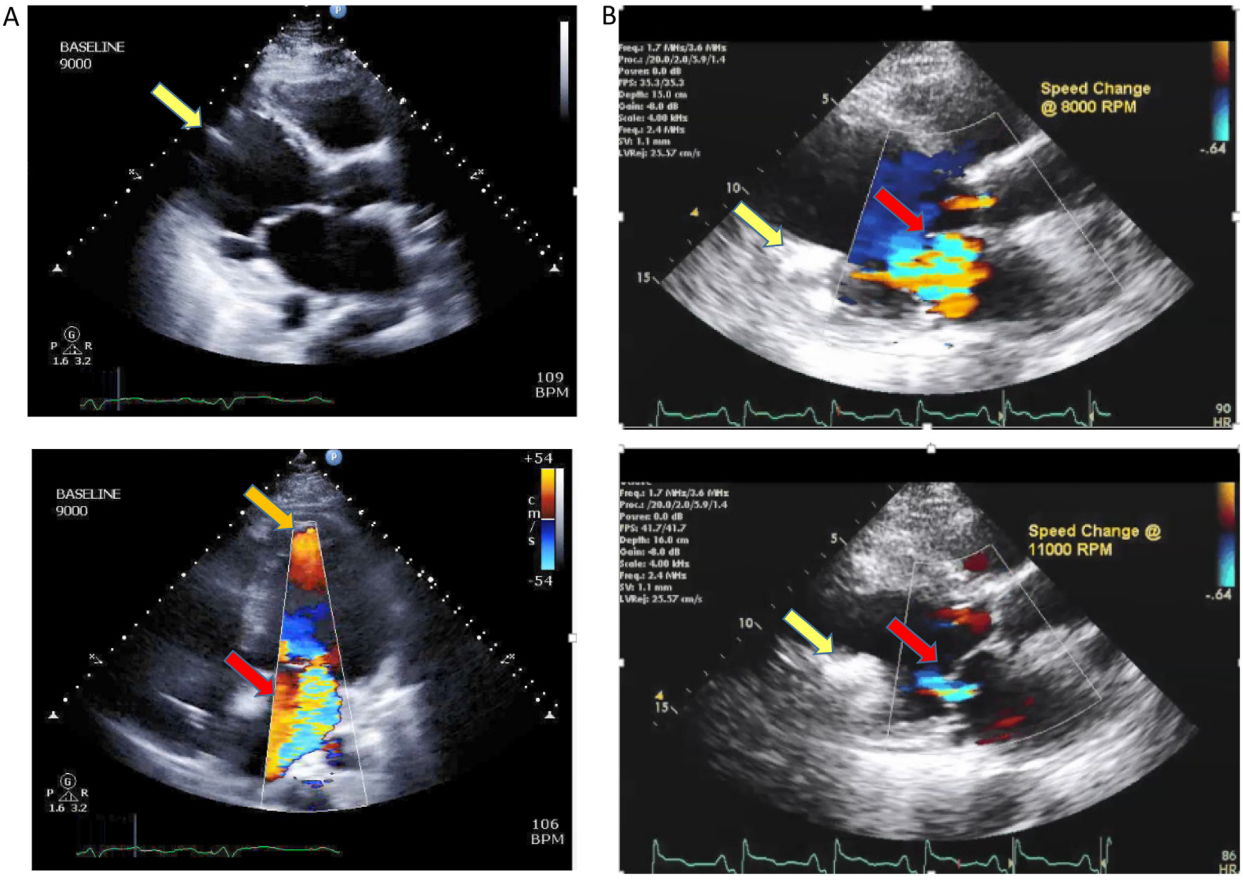


Figure 31 Transthoracic echocardiography–defined significant MR during HM-II support and guided optimization. **(A)** *Upper panel*: parasternal long-axis view with the HM-II inflow cannula (*yellow arrow*) in the normal apical position directed to the anterior MV leaflet. *Lower panel*: 4-chamber apical view with color Doppler demonstrating flow into the apical inflow cannula (*orange arrow*) and significant MR (*red arrow*) during HM-II LVAD support. **(B)** *Upper panel*: inflow cannula malposition noted in the midposterior LV position (*yellow arrow*) with tethering of the posterior MV leaflet and significant MR (*red arrow*) at a low pump speed setting (8,000 rpm). *Lower panel*: parasternal long-axis illustration of improvement in MR severity (*red arrow*) at a higher pump speed setting (11,000 rpm).

Table 5 LVAD/TMCS sonographer checklist worksheet

Ordering physician/team identified and documented contact information
Device type with device name noted on worksheet and annotated on screen along with device speed
Durable LVAD:
HM3 or
HVAD or
HM-II
TMCS device:
LV support
IABP
Impella CP or
Impella 5.5
RV support
Impella RP or
Impella RP Flex or
ProtekDuo or
Right heart pump (Abiomed or Centrimag)
Biventricular support
VA ECMO alone
VA ECMO plus LV support device above
RV support device plus LV support device
Study type being ordered:
Surveillance (no speed change or repositioning planned)
Problem solving at baseline speed only
Problem solving at baseline + other speed change testing
Recovery
Other key clinical history/information related to study indication noted
Device implantation date documented
Device alarms: if present, type of alarm identified
Low flow
High flow/high power
PI event
Suction and/or low volume alarm
Position alarm (wrong or unknown position, e.g., Impella devices)
Sudden pump stop
Anticoagulation therapy adequate if low pump speeds tested
Designated person and contact noted to change pump speed or reposition pump (Impella)
Device speed changes noted on worksheet and annotated on screen
Blood pressure (arterial line or cuff or Doppler) noted on worksheet and annotated on screen (obtained by trained individual at time of and after the exam if speed changes made)
Staff supervision: appropriate staff identified to perform speed changes; safety end point recognition (e.g., low flow, suction event, hypo-/hypertension); device repositioning
Identified reasons not to proceed with speed change or device position change
Aortic root thrombus detection (lowering speed could open AV)
LV thrombus (pushing in the Impella device and thrombus transit complication)
End point for speed change testing exams
Protocol completion
Change in clinical status (hypo/hypertension, new symptoms or signs)
Acquired device alarm during testing

(*Continued*)

Table 5 (*Continued*)

Ordering physician/team identified and documented contact information
Acquired signs of excessive ventricular unloading or suction event during the exam
Decrease in LV size (typically LV internal diameter <3 cm) or acquired small RV (right-sided devices)
IVS shifting leftward (left-sided devices) or rightward (right-sided devices)
Worsening of left and/or right shunting by color Doppler in the setting of VSD management
Cannula flow reversal with recovery exam at low pump speed

Key Points: Multimodality Imaging While on LVAD Support

- CCT with contrast and ECG gating provides the best visualization of the LVAD components and minimization of motion artifacts to optimize examination of the relationship between the LVAD and surrounding structures.
- CCT can detect malposition of the inflow cannula associated with dynamic myocardial tissue interaction with the inflow cannula.
- CCT is useful in the assessment of the outflow graft, especially in situations where low-flow alarms are related to the outflow graft kinking or obstruction by intraluminal thrombus or external compression.
- CCT is helpful to determine the position of the inflow and outflow cannulas and any bypass grafts or proximity of other cardiac structures to the sternum prior to LVAD explantation or exchange.
- FDG PET has diagnostic and prognostic utility to differentiate central (pump itself and/or the outflow cannula) from peripheral (driveline and/or the driveline exit site) LVAD infections.

Table 6 Durable LVAD low-flow alarm differential

Cardiac tamponade
RV Failure
Inflow cannula related:
Malposition and dynamic obstruction with the endocardium
Inlet obstruction due to thrombus, excessive trabeculation, or myocardial recovery
Outflow cannula/graft-related:
Twist
Kinking
Intraluminal thrombus
Extraluminal thrombus or biodebris
Other medical reasons:
Uncontrolled hypertension
Hypovolemia
Dysrhythmias (atrial or ventricular)

artifactual uptake, one should review the nonattenuation corrected imaging and, where available, metal artifact-reducing image reconstruction techniques, as noted above, should be used. Importantly, combination with contrast-enhanced CT may improve localization and diagnostic accuracy. Finally, the role of ECG-gated imaging is a key area for future investigation. Tagged leukocyte scintigraphy has been used for the diagnosis of known or suspected prosthetic device infections.[123,124] However, emerging data suggest poorer performance when using this technique as opposed to FDG PET.[114]

KNOWLEDGE GAPS AND RESEARCH NEEDS

Although novel measures of RV systolic function such as RVEF and indexed RV end-diastolic and end-systolic volumes by 3D echocardiographic assessment have emerged as predictors of early RVF after LVAD implantation, there remains a lack of data that defines the incremental role of using these measures in addition to RV strain and conventional RV echocardiographic parameters. Persistently elevated ventricular filling pressures coupled with a low cardiac output during LVAD or TMCS is associated with residual decompensated HF and adverse outcome. Two published diagnostic algorithms integrating standard echocardiographic parameters reliably distinguished between invasively measured normal and elevated LV filling pressures on baseline levels of LVAD support.[67,68] There remains, however, a paucity of data that defines the accuracy of echocardiography to detect partial LV and RV unloading while on TMCS. Moreover, there are no data to suggest that tailoring the pump speed setting to echocardiographically derived parameters in patients on an LVAD or TMCS is associated with improvement in clinical outcome. Best practices that incorporate clinical, hemodynamic, echocardiographic, and metabolic parameters for weaning from TMCS are currently poorly defined and not device specific. Future studies should explore optimal timing and strategies for deescalation and explantation of support. Although FDG PET imaging has proven diagnostic and prognostic utility, the effect of antimicrobial treatment on FDG uptake and subsequent clinical outcome remains unknown.

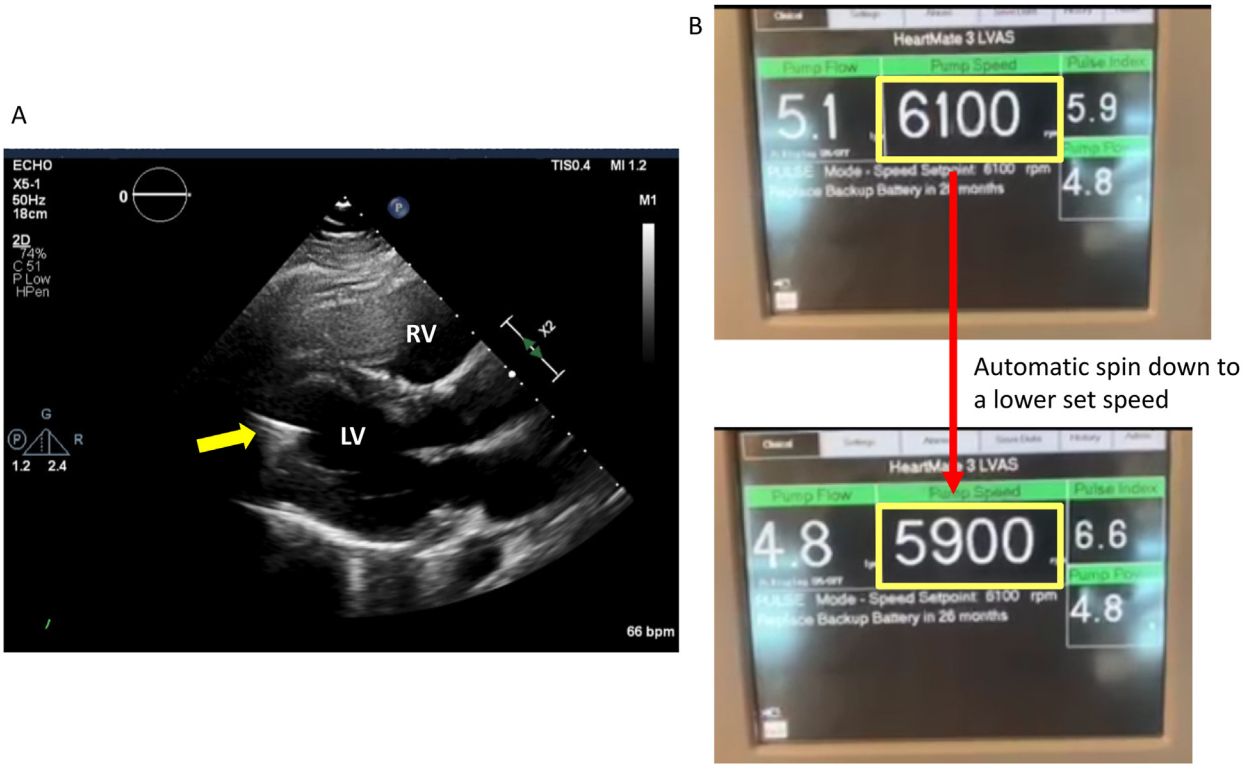


Figure 32 Low-flow alarm due to inflow cannula malposition. **(A)** Parasternal long-axis view with the inflow cannula positioned posteriorly (*yellow arrow*) with intermittent interaction with the endocardium associated with intermittent LVAD suction events as noted by **(B)** decrement in the HM3 set speed 6100 rpm to 5900 rpm along with a decrement in estimated flow from 5.1 to 4.8 L/min.

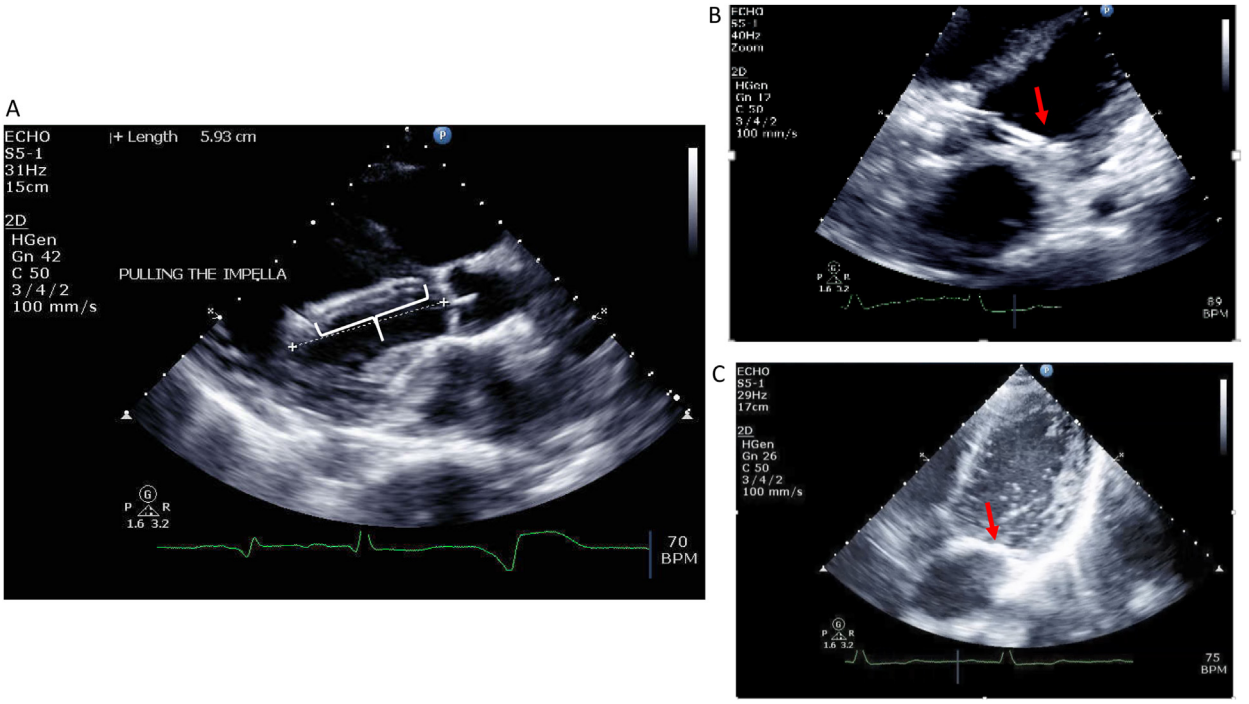


Figure 33 Transthoracic echocardiography–detected Impella-related complications. **(A)** Parasternal long-axis view in response to a suction alarm demonstrating the Impella device was too deep. **(B)** Five-chamber view illustration of Impella device malposition with the distal portion of the Impella device (*red arrow*) close to the mitral subvalvular apparatus and directed toward the base of the anterolateral free wall (*red arrow*). See movie 5. **(C)** Same patient as in *panel B* with detection of air bubbles in the LV confirming an air leak in the system.

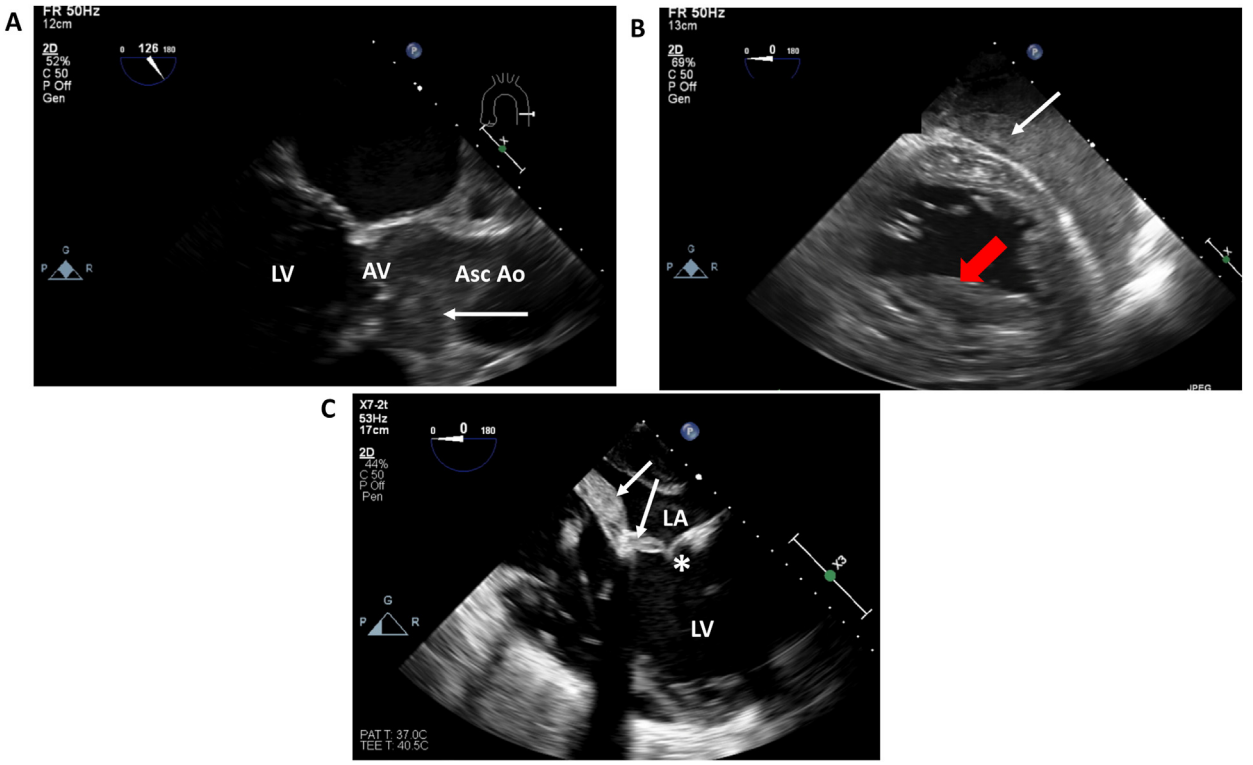


Figure 34 Transesophageal echocardiography–visualized thrombotic complications during VA ECMO. **(A)** Midesophageal AV long-axis view showing blood stasis and clot (*white arrow*) in the aortic root. **(B)** Transgastric short-axis view of the LV showing blood clot (*red arrow*) in the LV and within the pericardium (*white arrow*). **(C)** Midesophageal 4-chamber view showing blood clot along the LA wall (*white arrows*) and a newly placed prosthetic tissue valve in the mitral position (*white asterisk*). *AscAo*, Ascending aorta.

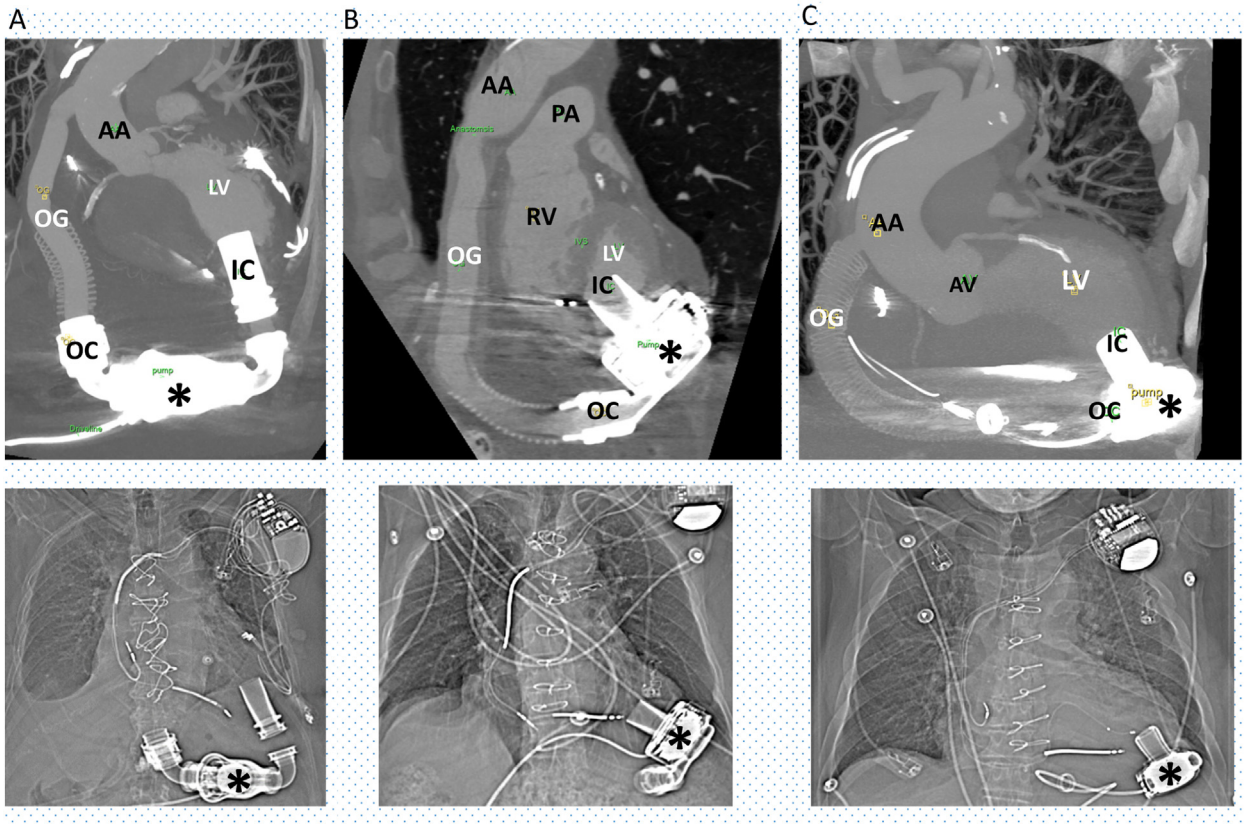


Figure 35 Left ventricular assist device components defined by CCT with contrast. (**A**) *Top panel*: HM-II inflow cannula placed in the LV apex and positioned parallel to the IVS. *Bottom panel*: the corresponding x-ray CT scout image. (**B**) HM3 inflow cannula noted to be directed toward the IVS. *Bottom panel*: the corresponding x-ray CT scout image. (**C**) HVAD inflow cannula positioned in the LV apex and parallel to the IVS. *Bottom panel*: the corresponding x-ray CT scout image. The *black asterisk* is the pump housing that contains the rotor. *AA*, Ascending aorta; *IC*, inflow cannula; *OC*, outflow cannula; *OG*, outflow graft.

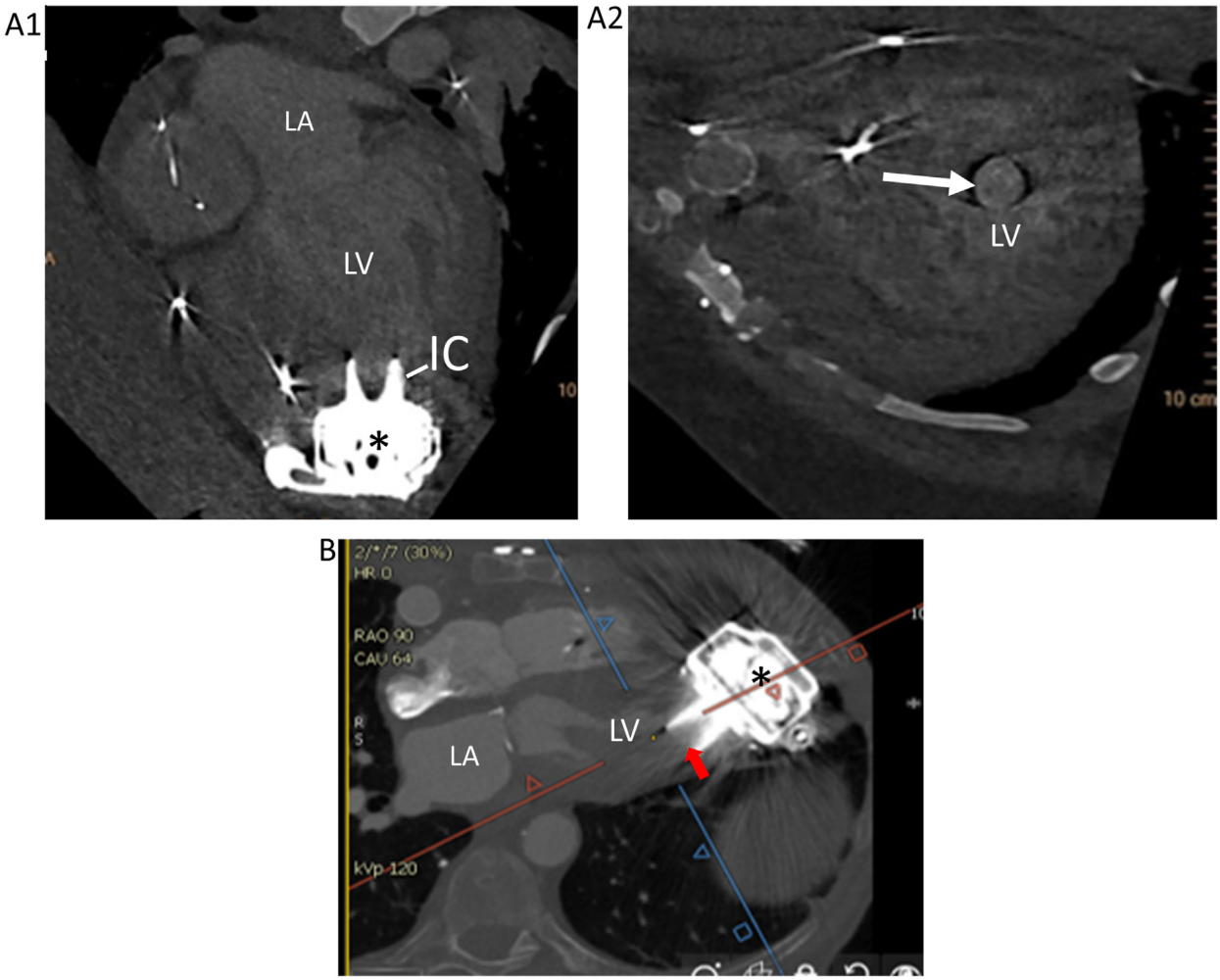


Figure 36 Gated CCT noncontrast illustration of normal and abnormal HM3 inflow cannula position. **(A1)** Long-axis view of the HM3 pump (*black asterisk*) and inflow cannula in the normal apical position directed toward the mitral inflow. **(A2)** Corresponding short-axis view with the inflow cannula (*white arrow*) noted within the center of the LV. **(B)** Four-chamber view with the HM3 pump (black asterisk) with noted inflow cannula malposition with direction toward the inferior LV wall and frank suction of myocardium into the cannula (*red arrow*). *IC*, Inflow cannula.

SUMMARY/DISCUSSION

Echocardiography and multimodality imaging, including CCT and nuclear imaging, are important in the management of LVAD patients (Figure 44). Although the field has evolved over the past several years, many of the recommendations made herein remain partly based on consensus expert opinion. Recommendation made regarding the role of echocardiography and multimodality imaging to manage LVAD patients align (with greater details provided herein) with those provided in the recent 2023 International Society for Heart and Lung Transplantation Guidelines for MCS.[25] There are specific echocardiography and CT parameters that constitute precautions before LVAD and TMCS placement. During and after LVAD and TMCS implantation, perioperative TEE and TTE, respectively, can be used to confirm normal versus abnormal device function and to determine whether the native heart is responding to LVAD or short-term device support as expected. We continue to emphasize a phase-of-care approach for all devices, which includes (1) preoperative assessment, (2) perioperative TEE for LVADs and selected TMCS devices, (3) postoperative surveillance echocardiography, (4) postoperative problem-focused echocardiography, and (5) recovery protocols.

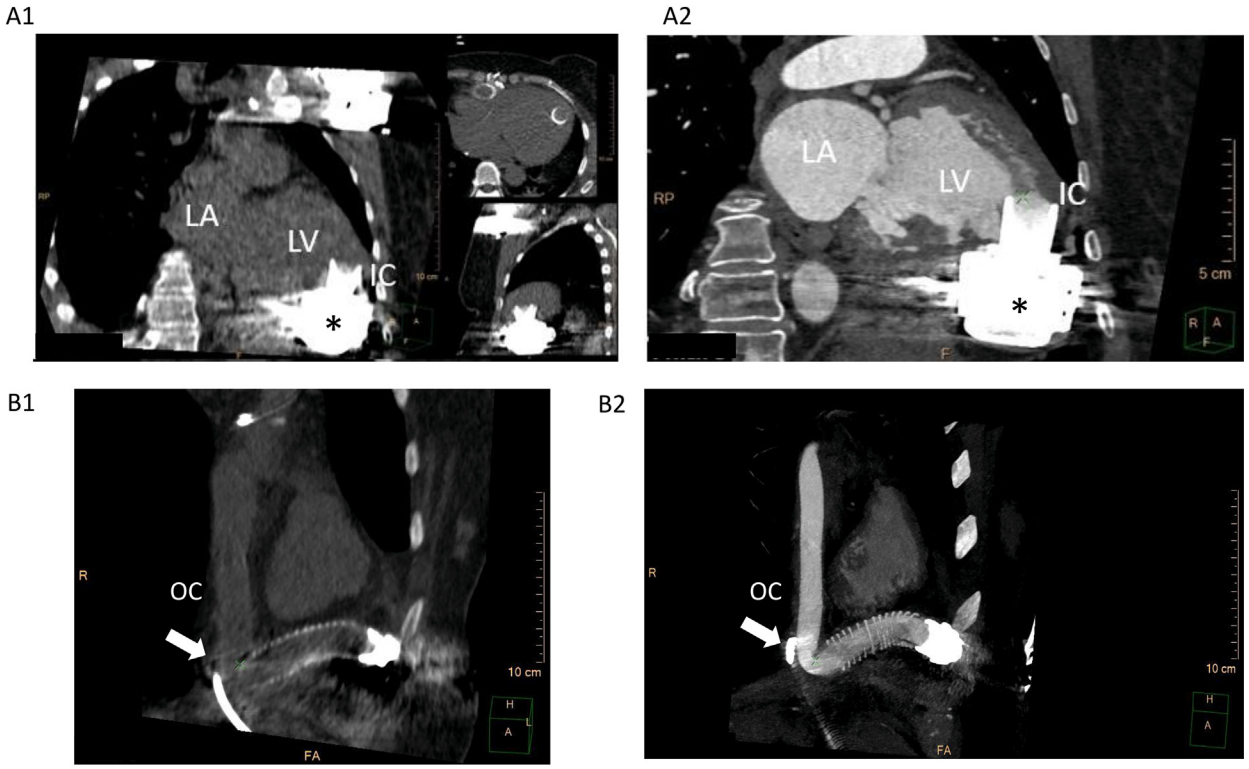


Figure 37 Left ventricular assist device inflow cannula and outflow graft assessment using gated noncontrast CCT versus contrast CTA. **(A1)** Gated noncontrast CCT (2-chamber view) illustration of the HM3 impeller housing (*black asterisk*) and the inflow cannula with malposition noted with the inflow cannula directed toward the distal anterior LV. **(A2)** Corresponding contrast CTA in the same patient with improved visualization and noted dynamic interaction of the inflow cannula and the endocardium. **(B1)** Gated noncontrast CCT with visualization of the outflow cannula and noted outflow graft kinking (*white arrow*). **(B2)** Corresponding contrast CTA in the same patient with improved visualization. *IC*, inflow cannula; *OC*, outflow cannula.

Another important concept that has emerged since the publication of the 2015 Guideline is the concept of "cardiogenic shock teams." Given the high morbidity and mortality associated with CS and the time-sensitive nature of highly specialized treatment, many centers have implemented multidisciplinary shock teams that include representation from cardiology, surgery, intensive care, and anesthesiology. The benefit for team-based care in critical illness has been demonstrated in many areas of medicine,[125] and similar evidence of improved survival and reduced resource utilization has emerged from the analysis of cardiac intensive care units' practice patterns and outcomes as well.[126] Therefore, an additional goal of this document is to provide a practical and readily available key reference for the CS team members who may or may not be experts in echocardiography, CCT, and nuclear imaging. Ideally, these individuals can use the concepts and recommendations including safety precautions to effectively communicate with referral centers when examining patients supported by both durable LVAD and TMCS devices. In conclusion, the writing group hopes that this document has enhanced the framework for better incorporating echocardiography, CCT, CTA, and FDG PET-CT into the care of patients with either durable surgically implanted LVADs or TMCS devices. We hope the current framework will improve patient outcomes by providing the best imaging strategies for both patient selection and management after device implantation. This document is also intended to stimulate validation and outcomes-based studies and to advance the field of MCS.

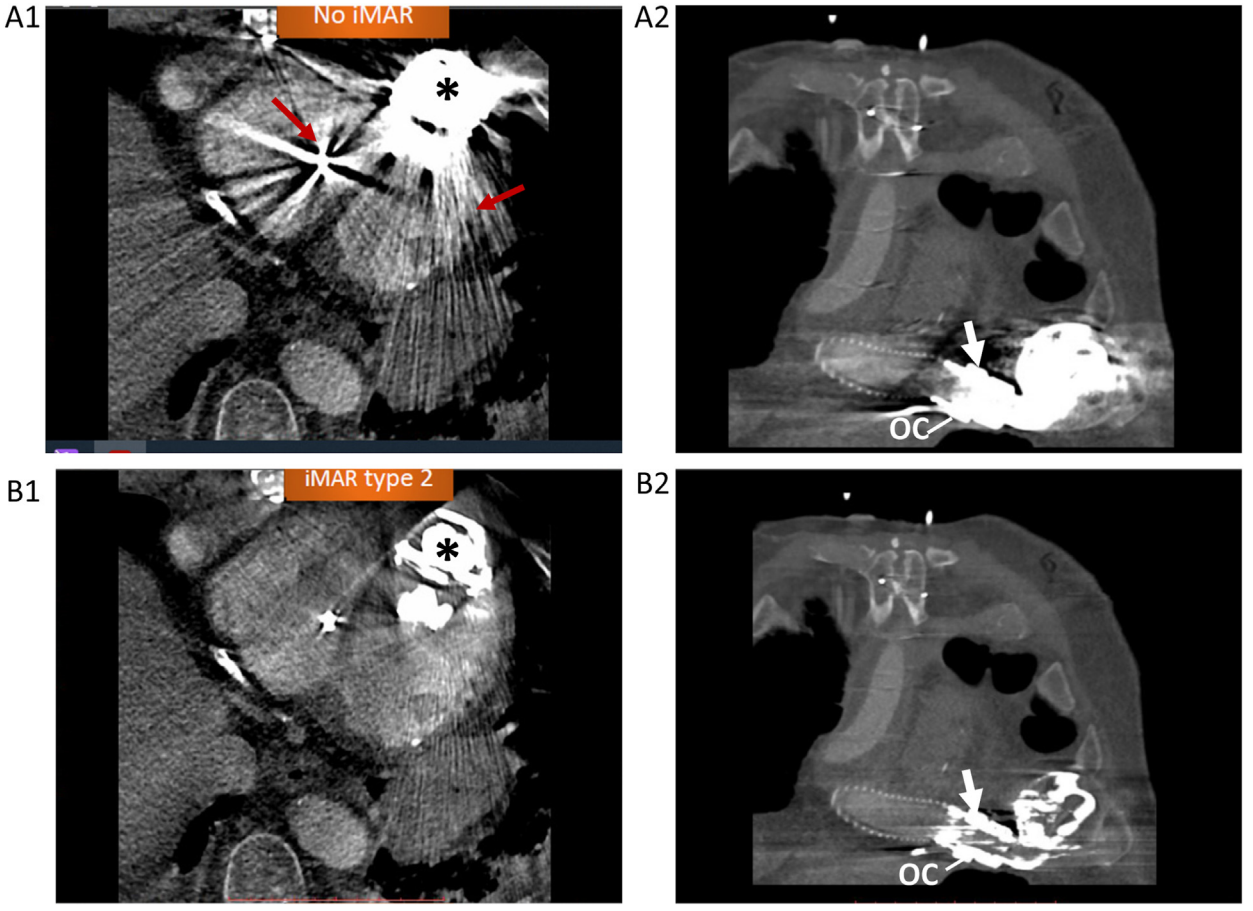


Figure 38 Reduction of metallic artifacts in a CT scan demonstrating HM3 image improvement. **(A1)** Illustration of LVAD-associated metallic artifact (*red arrows*) due to highly attenuating metal material (titanium alloy) within the pump (*black asterisk*). **(A2)** Illustration of limited visualization of the outflow cannula (*white arrow*). **(B1)** Application of an iterative metal artifact reduction algorithm and illustration of reduction in associated LVAD metallic artifacts from the pump (*black asterisk*) and improved **(B2)** visualization within the outflow cannula (*white arrow*). *OC*, Outflow cannula.

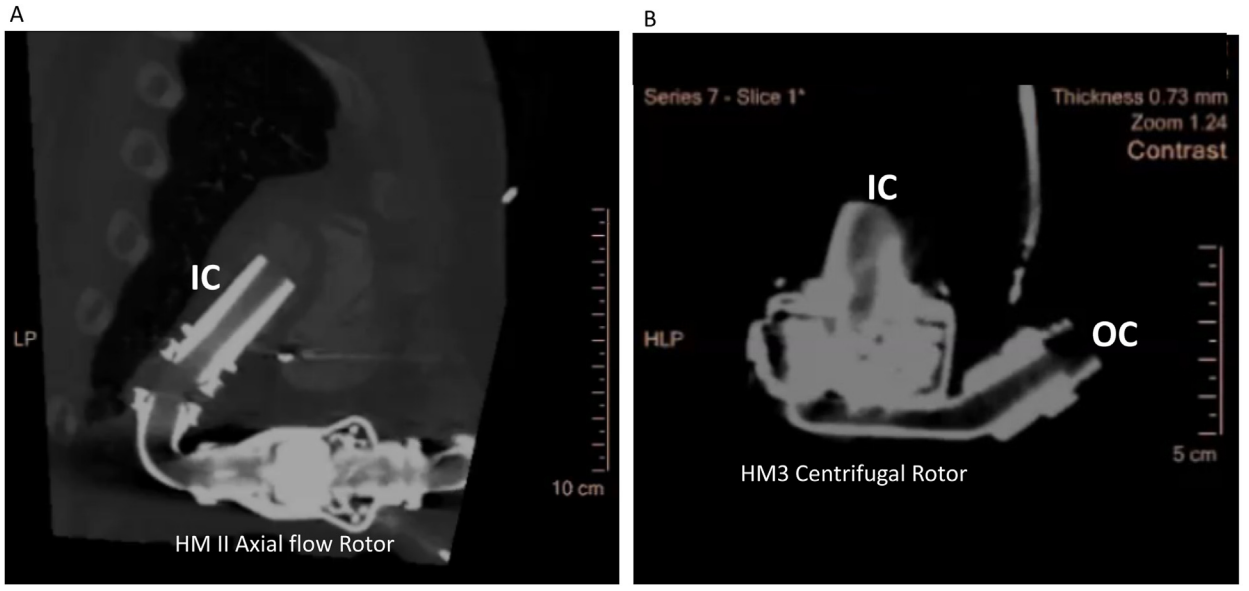


Figure 39 Computed tomography visualization within the HM-II and HM3 after contrast intensity window adjustment. **(A)** HeartMate II with axial flow rotor within the pump housing and nonobstructed flow from the LV to the outflow graft. See movie 6. **(B)** HeartMate 3 with a centrifugal fully magnetic levitated pump and nonobstructed flow from the LV to the outflow graft. See movie 6. *IC*, Inflow cannula; *OC*, outflow cannula.

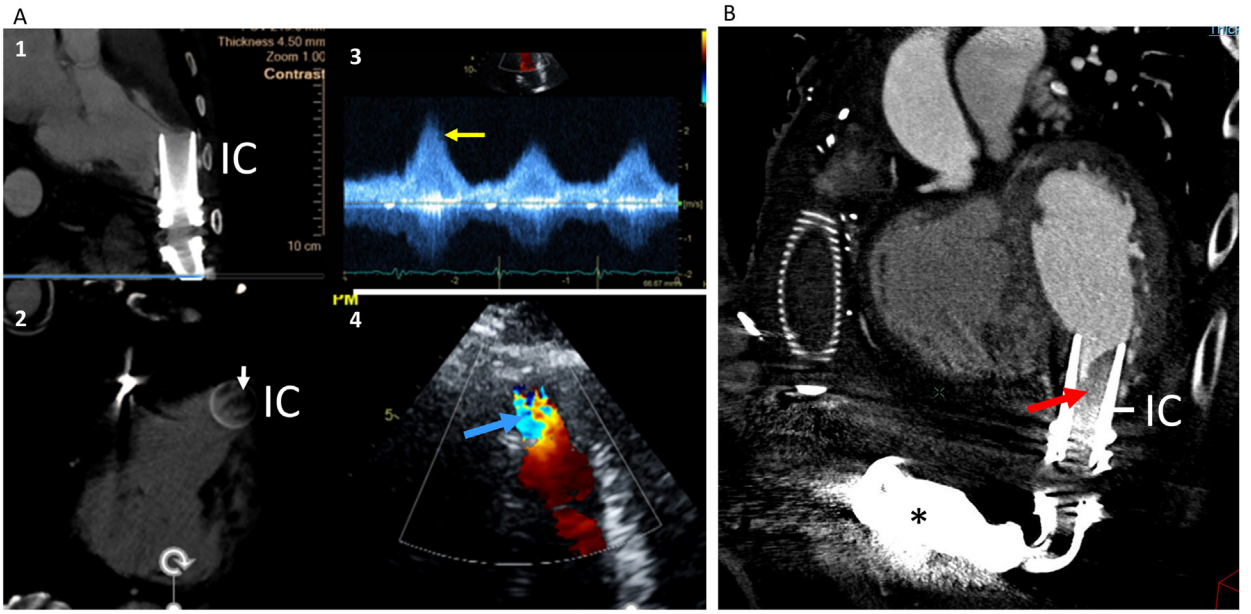


Figure 40 Cardiac CT and CTA detected HM-II inflow cannula malposition and thrombosis. **(A1)** Multiplanar reformatted long-axis view with the HM-II inflow cannula directed toward and abutting the distal LV anterior wall with **(A2)** short-axis view of the cannula tip noted in the anterior position with LV trabeculation sucked into the cannula (*white arrow*) and **(A3)** spectral Doppler interrogation of the inflow cannula showing elevated peak velocity above 2 m/sec (*yellow arrow*) with **(A4)** turbulent flow by CFD (*blue arrow*). (**B**) HM-II pump (*black asterisk*) with the *red arrow* showing low Hounsfield unit (HU) material consistent with thrombus within the inflow cannula. The HU is a relative quantitative measurement of radio density with low-density tissues assigned darker colors. *IC*, Inflow cannula.

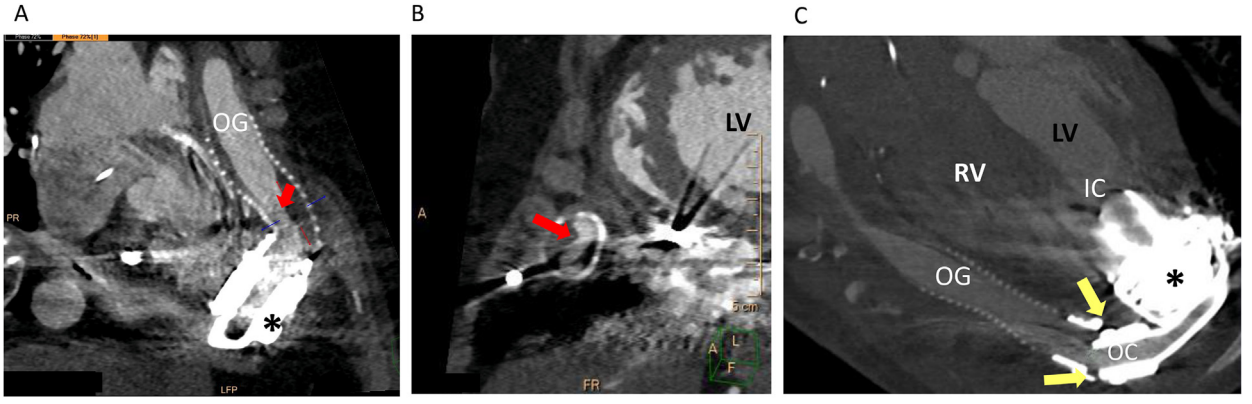


Figure 41 Computed tomography angiography–defined HM3 outflow graft twist and bend relief disconnect. **(A)** HeartMate 3 pump (*black asterisk*) with noted narrowing of contrast (*red arrow*) within the proximal portion of the OG due to suspected OG incomplete twist subsequent to rotation of the proximal portion of the OG. **(B)** Short-axis view of the proximal OG in the same patient further illustrating "twist" defined by the serpentine (tortuous) flow pattern (*red arrow*). **(C)** Bend relief disconnect (*yellow arrows*) showing disruption of the most proximal portion of the OG and OC connection. *IC*, Inflow cannula; *OC*, outflow cannula; *OG*, outflow graft.

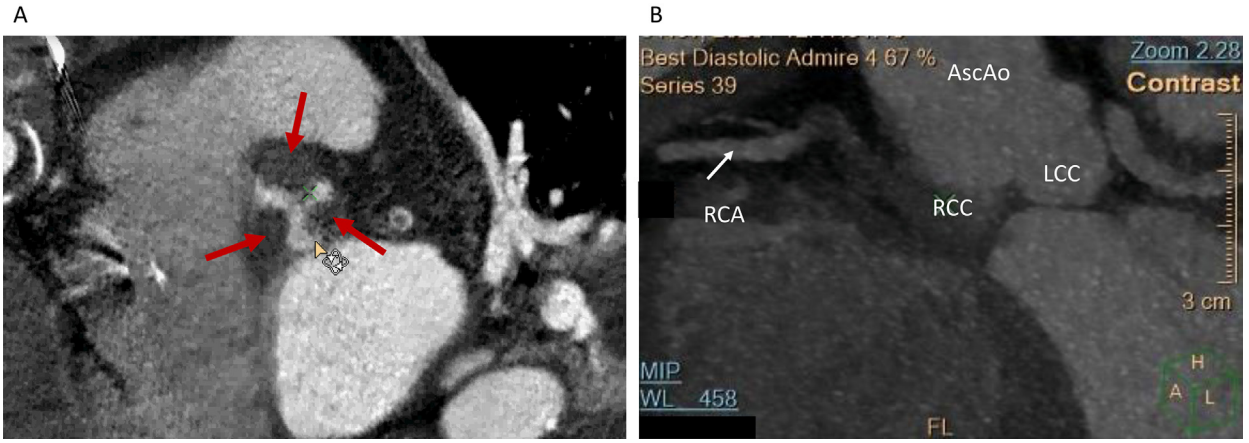


Figure 42 Computed tomography angiography–defined aortic root thrombus during LVAD support. **(A)** Short-axis view of an AV thrombus in all 3 aortic root sinuses (*red arrows*). **(B)** Visualization of right coronary clot extension into the ostium of the RCA (*white arrow*) with noted occlusion. *AscAo*, Ascending aorta; *LCC*, left coronary cusp; *RCC*, right coronary cusp.

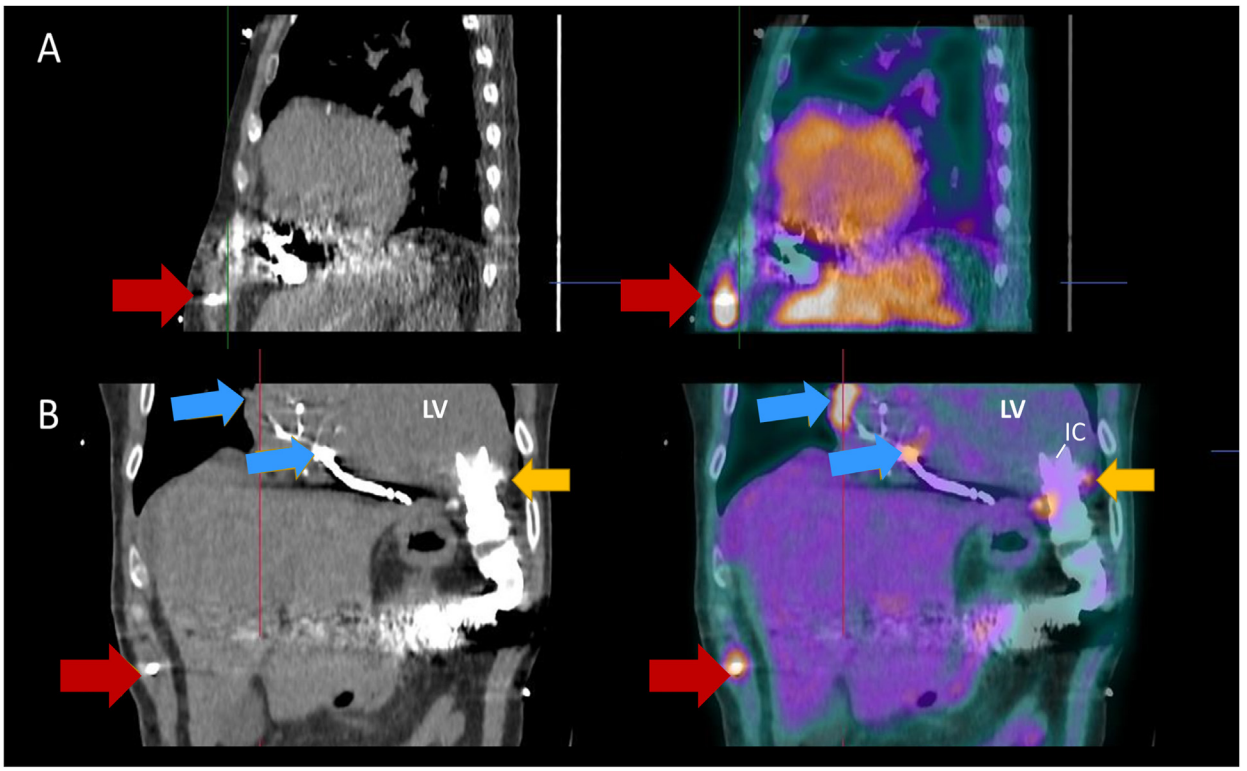


Figure 43 An FDG PET-CT illustration of LVAD-related infection sites. Two case examples **(A and B)** of a noncontrast attenuation CT (*left panels*) and corresponding PET-CT fusion images (*right panels*) indicating regions of abnormal uptake involving the LVAD driveline (*red arrows*). **(B)** Illustration of a concomitant central LVAD infection with abnormal uptake involving the inflow cannula (*orange arrow*). Also shown are regions of abnormal uptake in the cardiac implantable electronic device lead (*blue arrow*). *IC*, Inflow cannula.

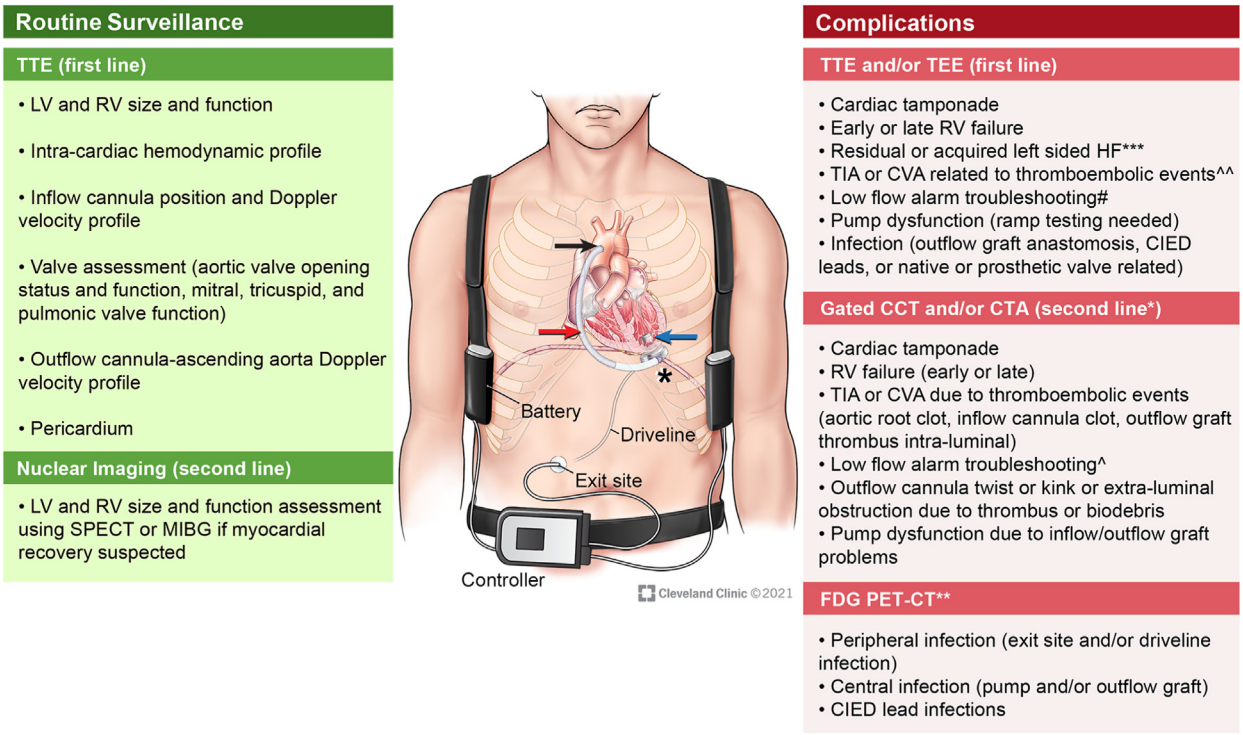


Figure 44 Role of multimodality imaging in patients supported by LVADs. *Consider in the setting of a nondiagnostic echocardiogram or further confirmation desired to facilitate surgical management. **Consider with recurring driveline infection or persistent or recurring bacteremia (see text). ***Due to significant AR or MR and/or inflow cannula malposition versus partial LV unloading related to the pump speed setting. ^^Related to thromboembolic events due to LV, LA, and/or aortic root thrombus (UEA use helpful). #Due to cardiac tamponade, RVF, or inflow cannula obstruction with or without malposition. ^Due to inflow cannula malposition or outflow graft twist, kinking, or intra- or extraluminal obstruction. The *blue arrow* marks the inflow cannula. The *black asterisk* marks the HM3 centrifugal pump. The *black arrow* marks the outflow graft anastomosis site. The *red arrow* marks the outflow cannula. *CIED*, cardiac implantable electronic device; *TIA*, transient ischemic attack; *CVA*, cerebral vascular accident; *MIBG*, nuclear I-meta-iodobenzylguanidine; *SPECT*, single-photon emission computed tomography.

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CONFLICTS OF INTEREST

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